JOURNAL OF GEOLOGY

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS

—

THE CAMBRIDGE UNIVERSITY PRESS
LONDON

THE MARUZEN COMPANY, LIMITED
TOKYO

THE COMMERCIAL PRESS, LIMITED
SHANGHAI

THE
JOURNAL OF GEOLOGY

A Semi-Quarterly Magazine of Geology and Related Sciences

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VOLUME XXXVI

JANUARY–DECEMBER, 1928

1928
R 550 v.36

THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILLINOIS

JUN 26 1929

Published
February, March, May, June, August, September
November, December, 1928

Composed and Printed By
The University of Chicago Press
Chicago, Illinois, U.S.A.

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THE

JOURNAL OF GEOLOGY

January-February 1928

INSTRUMENTAL WORK ON THE NATURE OF GLACIER MOTION

ROLLIN T. CHAMBERLIN
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ABSTRACT

In an endeavor to decide between viscous flow and crystalline yielding as the basic phenomenon in glacier motion, measurements of the internal shearing in glaciers were made with a self-recording clockwork apparatus. These automatic records show that slipping takes place along definite shearing planes, at times gradually and at other times by distinct jumps. The capacity to withstand a certain amount of growing stress before yielding is indicated. The results speak definitely for the solidity and elastic rigidity of moving glacier ice, and decisively against liquid or viscous flow as the main type of adjustment under stress.

Four manifestations of glacier movement are recognized: (1) solid flow by idiomolecular exchange between ice crystals, (2) solid shearing of aggregates of granules, (3) intermittent slip along well-developed thrust-fault planes, and (4) sliding of the whole body of ice over the rock beneath.

INTRODUCTION

Ever since Horace Benedict de Saussure made his famous ascent of Mont Blanc in 1787 and commenced those experimental and observational researches which attracted so much attention at the time, the nature of glacier motion has been a subject of much inquiry and debate. From time to time, as the science of geology progressed, various theories have been advanced to explain the movement of glaciers; but as yet none of these has met universal acceptance. In recent years the students of glacial phenomena have gradually gathered into two distinct schools: those who believe that

a glacier moves like a liquid of high viscosity; and those who insist that, because ice is a rigid, crystalline solid, it should behave as such during movement as well as at any other time. Those of the first group assume that a moving glacier partakes of the mobility characteristic of substances in the liquid condition. There are various modifications of the viscous theory, but they all come fundamentally to the same premise. Those of the other group, impressed by the crystalline nature of ice, which seems inconsistent with the liquid condition and liquid flowage, believe that the glacier as such must move as an elastico-rigid solid; and they appeal to solid flow and solid shear. "Solid flow" in this case means crystalline reconstruction chiefly by detachment of individual molecules from points of greatest pressure and reattachment at points of pressure-relief, technically known as molecular flow, or "idiomolecular transfer."[1] In addition to the declared adherents of the viscous theory and the distinct advocates of the idiomolecular theory, there are those who play fast and loose with both sides and entertain more or less vague notions of the mechanics of moving glaciers.

The problem.—In the hope of deciding with greater certainty between viscous flow and crystalline yielding, some instrumental studies were undertaken in the summer of 1910. The working criteria were as follows: If a glacier flows in liquid fashion, it should move steadily forward like a mass of tar, maintaining complete continuity. If, on the other hand, it maintains its crystallinity and elastic character throughout, it must move either by recrystallization or by shearing, or by a combination of these processes.[2] These methods of motion are sufficiently different to permit discrimination in the field.

It was demonstrated long ago that the upper portion of a glacier moves faster than the lower, but this has generally been interpreted as the effect of bottom friction on the continuous motion of a liquid. On the other hand, definite shearing planes were recognized years

[1] T. C. Chamberlin, "Diastrophism and the Formative Processes, XV. The Self-Compression of the Earth as a Problem of Energy," *Jour. of Geol.*, Vol. XXIX (1921), pp. 697–99.

[2] In this paper the term "shearing" will be used in its common sense to denote a different mass movement of the ice on opposite sides of a definite separation plane, and not according to the extreme use which makes it applicable to liquids.

ago in many of the Greenland glaciers, and these seemed to be characteristic features of glaciers.[1] If the portion of the ice above one of these shearing planes moves bodily over the ice beneath it, this phenomenon must be of prime importance in an understanding of glacier movement. By making the proper instrumental tests of this internal shearing, it was hoped that much decisive evidence could be brought to bear upon the question at issue.

The immediate objects of the experimentation were, first, to demonstrate mass movement along thrust faults, or shear planes, which would indicate rigidity and brittleness of materials; and second, if shearing were found to occur, to determine any relation which there might be between the rate of shearing and such factors as the mean temperature, the daily range of temperature, the amount of water entering the ice from melting or from rainfall, and other variable conditions.

If high temperature, or changes of temperature, melting and freezing, or other fluctuating surface conditions are important factors in glacial advance, they should affect a shallow zone near the surface of the glacier more pronouncedly than the main mass of the ice. A thin portion of the glacier above a shearing plane should therefore be expected to be more sensitive to these fluctuating conditions than the whole glacier moving over the valley floor. The studies were therefore directed to the shearing planes, and a graphic method of recording movement sought.

The apparatus.—To accomplish this, a self-recording clockwork apparatus was devised and constructed. This consisted of a brass barograph cylinder, $4\frac{1}{4}$ inches in diameter and $4\frac{1}{2}$ inches long, which was connected with a clock and so geared as to make one revolution in twenty-four hours. By means of attachments and supports, the clock and recording cylinder were made into one piece which could readily be clamped onto a rod driven into the glacier. In practice this rod was driven deep into the ice 8 or 10 inches below the shearing plane to be investigated, and was therefore anchored in the supposedly less rapidly moving portion of the glacier. To this rod was attached also the recording device, whose movable portion con-

[1] T. C. Chamberlin, "Recent Glacial Studies in Greenland," *Bull. Geol. Soc. Amer.*, Vol. VI (1895), pp. 205–9.

sisted of a long slender brass rod 18 inches in length, tipped by a silver point and capable of such adjustment that the silver point could easily be made to come in contact with the surface of the recording cylinder at any desired point. The record was to be written by this silver-tipped pencil, which traced a line upon a sheet of metal-paper wrapped around the cylinder of revolution.

A few inches above the chosen shearing plane, and hence in the supposedly more rapidly moving portion of the glacier, another rod was driven securely into the ice. Sliding along this rod was a metal bar of triangular cross-section which could be adjusted so as to bring a sharp edge in contact with the free end of the recording rod. Then, as the portion of the glacier above the shear zone was thrust forward more rapidly than the less movable ice below the shear plane, the sharp-edged crossbar on the upper rod was pushed steadily against the free end of the recording rod; and this, on the lever principle, caused the opposite end of the rod carrying the silver tip to mark a metallic line on the white metal-paper encasing the slowly rotating cylinder (Fig. 1). As the cylinder turned in just twenty-four hours, an autographic record of the day's shearing movement was readily obtainable. It was hoped that not only could a complete record of all variations in the rate of shearing be obtained for the twenty-four-hour period but also that, by changing the sheet of metal paper every day and rewinding the clock, the record might be extended for as long a period as the rods would remain securely in the ice.

The recording rod was held in a sliding socket which was made to clasp it at any chosen point throughout its length, thus making it operate like a lever. By making the arm carrying the silver writing tip ten times as long as the arm against which the thrust of the advancing upper portion of the glacier was directed, the amount of actual shear was magnified ten times on the automatic record. Thus an actual shear of the glacier amounting to one-tenth of an inch was, with this adjustment, represented on the record by a deviation of an entire inch. By virtue of such a magnification, the instrument was very sensitive and hence capable of detecting and recording shearing of the gentler sort. If the glacier were shearing more actively, the instrument could be readily geared so as to reduce instead of magni-

fying the motion. It was thus capable of ready adjustment to a wide variation in the rate of shearing movement.

FIRST TRIALS IN ALBERTA AND BRITISH COLUMBIA

Horseshoe Glacier.—During the month of August, 1910, this instrument was fastened upon a very conspicuous shear zone at the terminus of the Horseshoe Glacier near Lake Louise in the Rocky

FIG. 1.—Apparatus on Horseshoe Glacier. The recording cylinder and clock were attached to the ice below the shearing plane; the push against the lever came from the ice above the shearing plane. The lever was geared ten to one.

Mountains of Alberta. The Horseshoe Glacier is a small one lying at the base of the cirque whose high rocky ramparts constitute the head of Paradise Valley and culminate in the beautiful peaks of Lefroy and Hungabee. The cirque walls are so precipitous that little snow lodges upon them and the glacier is confined to the lowest slopes of the amphitheater and a short stretch of the valley beyond. It is therefore a thin sheet of ice whose upper surface is a very gently sloping plain. Because it is a thin, flat sheet, it was hoped that its

upper portion would be more sensitive to fluctuating meteorological conditions than would be the case in a more massive glacier.

An examination of the terminus of this glacier revealed a very pronounced horizontal fracture plane where the upper ice projected forward into space beyond the margin of the lower ice, overhanging it in places as much as 2 feet (Fig. 2). This overhanging was impressive and seemed to imply that the upper ice was then sliding, or had

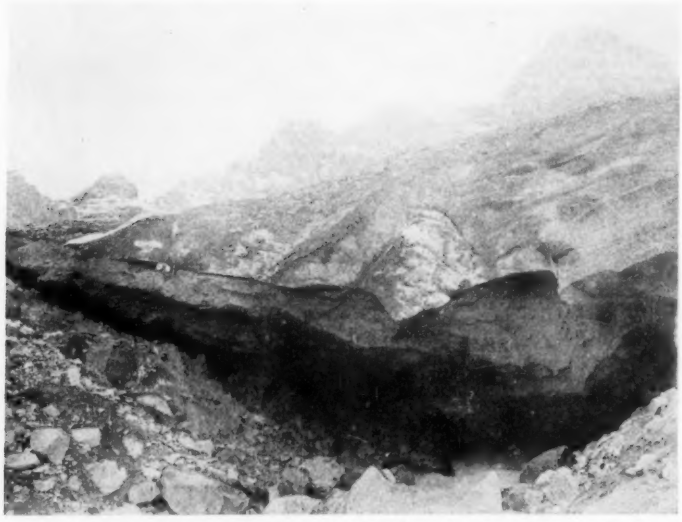

FIG. 2.—Instrument recording movement along shearing plane in Horseshoe Glacier, Canadian Rockies. August, 1910.

very recently slid, strongly over a less movable portion below. A reason for this was readily seen in the resistance which the morainic dumps offered to the basal portion of the ice, while the upper portion was freer to move forward. In addition to this, the lower ice was heavily charged with débris which necessarily retarded the motion, while the upper ice contained very much less débris and in consequence was much freer to move. As Figure 1 shows, this seemed a very promising place for experimentation on shearing.

The instrument was kept in operation on this supposed shear

zone for seven days. Various unexpected minor difficulties were encountered which emphasized the observation that experimentation on glaciers is quite different from working in a laboratory, but they were more or less overcome. The total result for the seven days, however, was a straight line on each day's sheet. As the recording needle was geared 10:1 these straight lines indicated that the shearing did not exceed a hundredth of an inch during any one of the days of the experiment. This was equivalent to saying that there was no appreciable shearing along this plane during this week in August.

One explanation offered for this seeming anomaly is that the protrusion of the upper ice beyond the edge of the lower ice was not due to shearing at all, but was merely because the débris-laden lower ice had melted back more rapidly than the cleaner ice above the fracture plane. The alternative explanation is that the shearing process had already been completed at that place for that summer. The process may have operated somewhat as follows: In the spring of the year the winter snows resting upon this small, flat glacier began to melt. The resulting water in part flowed away on the surface and in part sank into the glacier. Such as entered the cold ice presumably became frozen. As the spring advanced and the days became warmer, the zone affected by the descending water became progressively deeper. With more water in the ice, and more ready melting and refreezing, the upper zone became predisposed to move while the lower portion of the glacier had not yet been quickened to life. A tendency of the upper portion to shear over the lower might be expected. In fact one might expect to observe progressive shearing along several planes, each lower than the preceding. If this be the true explanation, the month of August was too late in the season to catch this process in operation. The results might still be visible, but the movement itself was past.

Asulkan Glacier.—The Asulkan Glacier in the Selkirk Range of British Columbia a few days later gave no better results than the Horseshoe Glacier.

TRIALS IN ALASKA

Whatever may have been the cause for the failure to get automatic records of shearing on the Horseshoe and Asulkan glaciers, it seemed in any case desirable to repeat the experiments on these,

or other, glaciers earlier in the season before the melting had progressed so far. After eight summers devoted to other work, the project was revived in 1919 by a study of certain of the rapidly moving glaciers of Alaska. For this study the glaciers along the Copper River seemed to offer the most promise, as some of them were known to combine rapid motion with a fair degree of accessibility, and at the same time to terminate on land and not in steep, iceberg-producing, sea-cut cliffs. Cordova was reached on June 30, and the journey inland to Childs Glacier made on July 1.

Childs Glacier.—In the vicinity of Miles Glacier Station, 48 miles from Cordova, on the Copper River and Northwestern Railway, there are two very active glaciers from which, during the summer, large masses of ice become detached and tumble into the river every few minutes. These are Childs Glacier, west of the Copper River, and Miles Glacier, east of the river, whose widened portion here is called Miles Glacier Lake. These glaciers are rapid movers and have been a source of considerable anxiety to the officials of the Copper River Railway, for in 1910 and 1911 Childs Glacier, during a spell of vigorous movement, threatened to sweep away the splendid $1,500,000 railway bridge which spans the Copper River, and stop all traffic on the railroad. In the spring of 1909 the northern margin of Childs Glacier was 3,440 feet from the bridge. By October 5, 1910, the ice margin had covered more than half of this distance and stood only 1,571 feet from the bridge.[1] Fortunately the advance rapidly slackened in 1911 and the bridge was saved. On November 28, 1914, the ice front stood 1,400 feet from the bridge, according to the map made by the railway engineers.

This very active and accessible glacier was naturally the first one visited. Unfortunately for the special shearing determinations, the most rapidly moving portion of the ice was excessively crevassed, which rendered most of its surface inaccessible without great labor and some peril. The phenomena of shearing were also greatly interfered with by the crevassing. The less crevassed portion of the glacier, which happened to be the northern tongue which threatened the bridge, was moving very feebly in 1919 and, while exhibiting

[1] Tarr and Martin, *Alaskan Glacier Studies* (National Geographic Society, 1914), p. 405.

distinctive shear at many points, did not afford the most promising situations for locating the instrument.

Grinnell Glacier.—Situations which appeared more promising were found on Grinnell Glacier, whose terminus is about 3 miles farther north. Grinnell Glacier collects in a flattish basin in the midst of the rugged Chugach Range and then moves down a steeper slope. Near the foot of the cascade, where the ice encounters more resistance, it is subjected to strong compression; and shear zones have become conspicuous. The most declared of these consisted of the usual fracture plane above which the upper ice of the ice cliff had been thrust bodily forward so as to project, as much as 3 feet in one case, beyond the ice just below the fracture plane. Some of the best cases were located on nearly vertical ice cliffs and were hardly available for so extended an operation as the anchoring and careful adjustment of the sensitive clockwork apparatus. A more favorably located shear plane was finally found and the apparatus set up. Profiting by the experiences of 1910 in the Canadian Rockies, holes of slightly smaller diameter than the rods were first bored into the ice with a long auger. Instead of the steel rods which had caused too rapid melting of the adjacent ice, wooden rods were now driven into the prepared holes and somewhat farther so as to anchor them firmly in the ice. The recording pencil was geared so as to magnify the actual shearing ten times.

The results were quite disappointing. Owing to continuously mild temperature, melting progressed at an unexpectedly rapid rate. This melting affected not only the glacier surface but also the ice in contact with the wooden rods, which allowed them to settle enough to influence the adjustment and vitiate the results. Unless both rods remain rigidly in place, the recorded lines cannot be relied upon. One of the unlooked-for disadvantages of the Alaskan glaciers for studies of this sort quickly became apparent. Experiments of this sort, other things being equal, should be most successful where the daily range of temperature is greatest. In the cloudy and rainy Chugach Mountain region of Alaska, where in early summer it does not get dark even at midnight, the daily range of temperature is not great. Unless the sun pierced the clouds, the thermometer at Miles Glacier Station seldom registered higher than 13° C. during the day or

lower than 8° C. at night. There was thus neither freezing at night, as there had been on the Horseshoe Glacier, nor any very pronounced change of temperature during the twenty-four hours. The ice was melting all the time. The results as they were, indicated very little actual shearing at the time of the experiment.

Kennecott Glacier.—The instrument was subsequently placed on what appeared to be a pronounced shear plane in the Kennecott

FIG. 3.—Prominent shearing plane on front of Shoup Glacier, Alaska

Glacier among the Wrangell Mountains farther from the coast. The records obtained indicated shearing of the upper ice over the lower, and they appeared to indicate that shearing was more pronounced between 6:00 P.M. and midnight than between 6:00 A.M. and noon. But here again, in spite of precautions, the melting of the ice rendered the immobility of the supporting rods not above suspicion and weakened greatly one's confidence in the verity of the results.

The results, however, seemed to be corroborated in a way by the "sloughing off" of Childs Glacier. Along several miles of its front this great glacier ends in a nearly vertical ice-wall, 200–300 feet high, whose basal portion is washed by the swift Copper River.

During the summer months, masses of ice weighing up to hundreds of tons break off with great frequency and go crashing down into the river, setting up a roar which can be heard several miles away. As a result of nine days and nights spent by Mr. Ben Herzberg and the writer within hearing distance of this ice front, we feel safe in saying that the falling of the ice masses from the cliff as the glacier moved forward was most conspicuous in the evening. The roar in the evening at times was almost incessant and profoundly impressive. The more rapid sloughing off in the evening would seem to have been the lagging result of more rapid melting, or more water in the ice, which facilitated movement and made it easier for masses to break off.

Tarr and Martin state that the sloughing off is due to undercutting by the Copper River.[1] This is no doubt the ultimate cause, since, if the river were not there to remove the ice, the glacier would spread out in a gradually sloping front and sloughing would cease. The river undercuts and also removes the fallen blocks of ice, thus serving a very necessary function. But it was also our observation that an overwhelming proportion of the ice masses which broke off came from the upper portion of the ice cliff and that the majority of the scars left on the cliff extended only about halfway down. The upper portion of the glacier was moving faster than the lower portion; and as it was also more broken by crevasses, the masses broke off in greatest abundance from the upper part and tumbled 200 feet into the river. It was a phenomenon suggestive of brittleness and rigidity.

TRIALS IN THE ALPS

The apparatus.—As the result of the experience gained from these unsuccessful trials on glaciers in the Canadian Rockies, Selkirks, and Alaska, an entirely different apparatus was constructed and the classic ground of the Alps selected for further advancement of the investigation. In the new apparatus, clockwork turned an aluminum disk, $5\frac{1}{2}$ inches in diameter, around in twenty-four hours. A circular sheet of paraffined paper, fitted on to this disk, served as the recording sheet. Above this was fitted another aluminum disk, 3 inches in

[1] *Op. cit.*, pp. 402–5.

diameter, having on its periphery twenty-four notches, one for each hour of the day. The sharp points of two recording needles, working as levers, scratched telltale lines on the paraffined sheet as this sheet, firmly held between the aluminum disks, made its daily revolution. One of the needles traced the notched outline of the smaller disk, thus automatically marking off each of the twenty-four hours. The other needle, receiving through a lever the thrust of the more rapidly

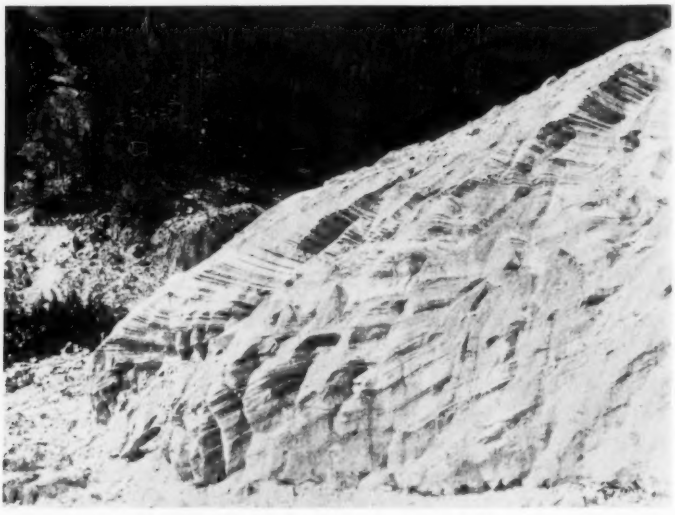

FIG. 4.—The terminus of the Glacier de la Brenva, Italian side of Mont Blanc. May, 1921. Shows the change in inclination of the secondary banded structure in relation to position.

moving part of the glacier, recorded faithfully the differential movement (Figs. 10 and 11).

Each completed record sheet thus contained two lines scratched in the paraffin: (1) a circle 3 inches in diameter with twenty-four notches giving the time of day, and (2) another line which would be a true circle (between 3 and 5 inches in diameter) if there were no differential movement of the ice. But if there were any movement of the ice along the shear plane under investigation, a corresponding displacement of this line resulted. All the working machinery was

built into a thin brass box to protect it from the outside weather (Fig. 9).

The method of attachment to the less movable ice below the shearing plane to be investigated was a distinct improvement upon the earlier methods. Steel tubes of $\frac{3}{4}$-inch bore, open at one end and drawn to a sharp point at the other end, which was strongly reinforced, were adopted instead of solid steel bars. Greater firmness

FIG. 5.—Banded structure along left side of Brenva Glacier not far from terminus. Structure planes dip in toward middle of glacier.

was secured by using two such tubes as supports instead of the single rod as before. A single rod may turn, but two supporting tubes several inches apart when the recording box is attached to them by double connection cannot. The box was held rigidly. The two hollow tubes, in addition to being driven deep into the ice, were also frozen to it by filling the tubes with a freezing mixture of salt and ice.

Brenva Glacier.—On the Italian side of Mont Blanc is the splendid Glacier de la Brenva. It was a surprise to find in May, 1921, that this glacier extended considerably farther down the valley than

it had during an earlier visit in 1909. Advancing strongly and showing evidence of vigorous ice action, it seemed favorable for shear-meter studies. On no other glacier has the writer seen the upturned shearing planes more strikingly shown than on the snout of the Brenva in 1921 (Figs. 4, 5, and 6). Several hundred yards back from the terminus, on the steep left wall of the glacier and about 50 feet above its base, there was a well-developed thrust-fault plane which

FIG. 6.—Banded structure of terminal portion of Brenva Glacier. Structural planes dip upstream.

gave evidence of recent slipping and which was made accessible for experimentation by a large shelf in the ice cliff just below the fault plane. This was chosen as the place for the experiment (Figs. 7 and 8). The shelf was found to be covered with a thick coating of débris. Preliminary inspection seemed to imply that while the shelf and the 50 feet of ice visible beneath it were moving forward at a fair rate, the ice above the fault plane was advancing even more rapidly because it encountered less resistance in front. This appeared to be, therefore, an ideal situation for measuring the internal differential movement.

An operating room was cut in the ice just above the shear plane, and two holes bored into the upstream wall for the tubes which were to support the apparatus. The tubes were filled with ice and salt, hammered rapidly into place, and the shear-meter box firmly attached by four screw-clamps (Fig. 9). The shear-meter thus advanced with the more rapidly moving ice above the shear plane, instead of being anchored in the ice below the shear plane as in

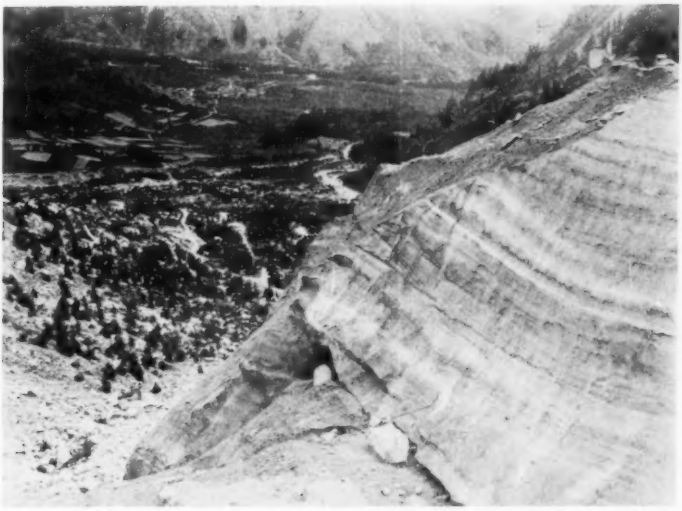

FIG. 7.—Prominent shearing plane and débris-covered shelf utilized in the experiments. The boulder and scantling show near the bottom of the picture. The shelf is about 50 feet above the bottom of the ice cliff.

previous trials. Contact with the slower-moving ice beneath the shear plane was accomplished as follows: A large boulder (4 by 3 by 2 ft.) was found to be resting securely in a veneer of débris sufficiently thick to reduce the melting of the glacier below to a minimum. The boulder was thus believed to be sufficiently fixed to the lower mass and sufficiently immobile for a reliable measurement. One end of a scantling (7 ft. by 2 in. by 1 in.) was placed on the boulder, and the other end was carefully adjusted so as just to touch the push lever of the meter. Slabs of rock piled on the boulder end of the

scantling held it rigidly to the boulder and thus to the 50 feet of ice below the shear plane. As the shear-meter moved forward with the ice above the shear plane, it pushed its lever against the end of the more slowly moving scantling, which moved with the lower portion of the glacier (Fig. 9). The backward push of the lever was, therefore, a measure of the differential movement; and this was recorded, magni-

FIG. 8.—Closer view of "workshop." The shear-meter is in place, but only the tip of one of the vertical attachments is visible, since the apparatus was anchored in the wall of a cave cut in the ice.

fied ten times, on the record sheet. Being on the wall-like east side of the glacier tongue, the ice here was exposed to the sun during the morning; while from the early afternoon on it was in the shade.

INSTRUMENTAL RESULTS

Figure 10 gives one of the records obtained. Line *A*, starting at 7:00 P.M. on June 2, departed very little from a circle for two hours, indicating practically no differential movement along the shear plane during that time. Then a slip forward occurred, followed by gradual

yielding for nearly three hours, after which came another sudden displacement. This caused the needle to run off the record sheet.

On the following morning the needle was reset on the record between ten and eleven o'clock. The course of the needle in this trial (line *B*) showed more uniform movement interrupted by minor slips. Shortly before one o'clock the needle ran off the disk and was reset.

FIG. 9.—The shear-meter in operation. The movement of the ice above the shearing plane (at base of visible ice) was toward the camera. The shear-meter was pushed by the upper ice against the end of the scantling, which was immovably attached to the lower ice by the boulder resting on the thick covering of débris.

Line *C*, which followed, likewise indicated movement by fits and starts.

Before leaving the glacier in the evening, record sheet No. 5 (Fig. 11) was put on the disk and a new run started at 6:45 P.M. When the station was again reached on the morning of June 4, line *D* was found to be the result. The pronounced zigzags of this line showed that there had been some periods of very little movement alternating with brief periods of rapid movement.

Line *E*, commencing about 10:30 A.M., also revealed some fairly

uniform motion interspersed with briefer periods of quicker movement.

Another trial beginning at one o'clock showed jumpy movement till a storm set in, when the whole apparatus was packed up and brought down to Courmayeur.

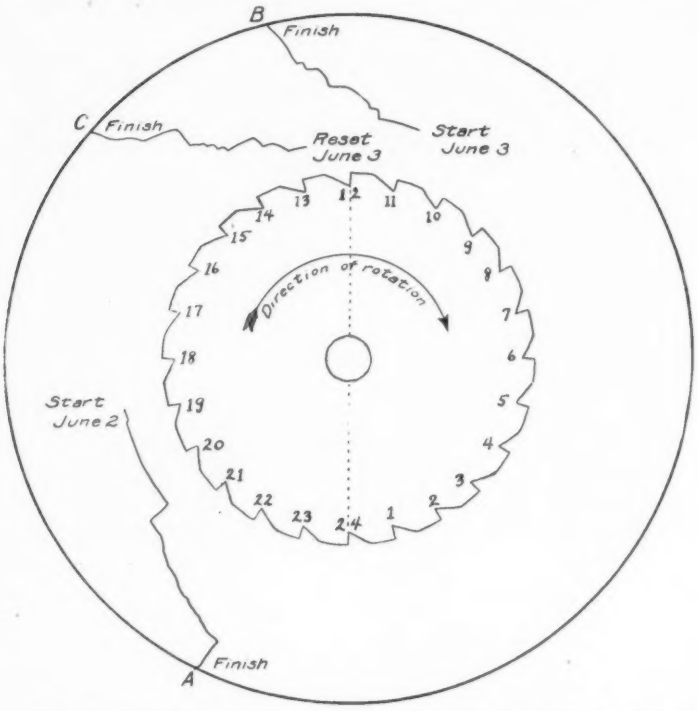

FIG. 10.—Copy of one of the records, June 2–3, 1921. $\frac{3}{4}$ actual size. A, B, C are the zigzag lines representing the shearing. The outward radial component of movement on the record multiplied ten times the actual movement along the shearing plane of the glacier. Time of day starting from midnight indicated by numbers on inner notched disk.

INTERPRETATION OF THE RECORDS

The significant peculiarity of these traced lines is the prevalence of small jumps at intervals. At times there was almost no differential movement of the ice; at times there was a slow, steady shearing of

the upper ice over the lower; while at other times there was a rapid slipping of the upper ice over the lower. The differential movement was thus quite variable, but none of the slips were large displacements. This leads to the conclusion that ice, under the conditions

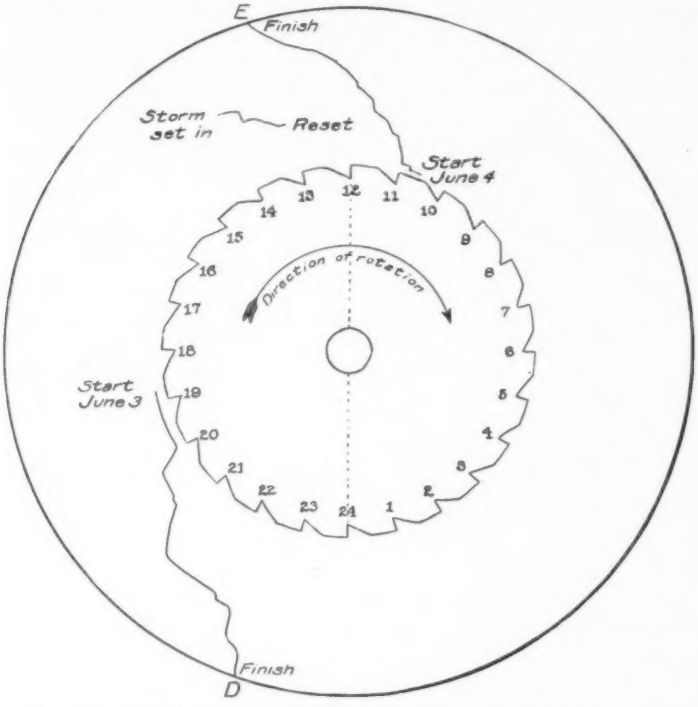

FIG. 11.—Copy of record, June 3–4, 1921. Lines D and E are the automatic traces of the shearing movement. Scale and magnification of movement same as in Figure 10.

that here obtained, yields readily to stress, so that no great accumulation of stress can take place without causing adjustment. And this inference from these specific records justifies the general inference that easy and frequent adjustment is characteristic. It is apparently because of this easy and frequent adjustment to stresses that the glacier seems to the eye to "flow" steadily down the

valley. But, though the adjustment is easy and frequent, it is not uniform. It is not only highly variable but changes its rate in individual parts frequently and spasmodically. This is sharply at variance with continuous liquid and especially viscous flow.

THE INTIMATE NATURE OF THE YIELDING

The fundamental question here raised is the intimate nature of this yielding under stress. If it were by liquid flow, especially if it were by viscous flow, the adjustment should be continuous and the lines scratched by the needle would be smooth curves without zigzags. This is not the case. Instead, the lines are made up of numerous jogs and indicate movement by a succession of small jumps, or little elastic accumulations and reliefs. Interpreted in terms of mechanics, this means that, incidental to the general movement of the glacier, differential stresses develop locally until the stress difference becomes sufficient to cause local readjustment, either by sudden slip along a fracture plane or by relatively rapid yielding for a short period of time. Since the capacity for storing up stress till the point of yielding is reached is a property of an elastic solid, and not a liquid, elastic solidity of material, i.e., material so organized as to have elasticity of form like a true rock, is indicated. Compared with most rocks of the lithosphere, however, the strength of the ice in these experiments was small and the adjustments frequent. These automatic records of the internal shearing, therefore, speak definitely for the solidity and elastic rigidity of moving glacier ice. They speak decisively against liquid flow as the main type of adjustment under stress.

GENERAL STATEMENT OF GLACIER MOTION

What may now be said of glacier motion in the light of current theories and these instrumental results? In the first place, it is to be remembered that the shear-meter recorded the movement along an unusually prominent shear plane which was in fact a well-developed thrust fault. The movement was typical of its kind, but all glacier motion is not slippage along fault planes. These automatic records cover only one type of manifestation of glacier motion. They do not cover the whole problem. Their importance lies in proving the

accumulation of stress and intermittent shearing of solid masses. But this very fact is of critical importance, for it shows that the common conception of viscous liquid flow has to be eliminated from the picture completely before any real understanding of glacier motion is possible.

THE BASIC PROCESS

The general nature of glacier motion has been well described by T. C. Chamberlin.[1] The growth of ice granules, together with slight movement and adjustment between the granules under changing pressure conditions, is considered to be the underlying basic phenomenon. Compression produces heat and at the same time lowers the melting-point of ice. Compression becomes greatest at certain points of contact between granules. Liquefaction of minute portions of the granules will occur at the points of greatest compression; and, moving to points of less compression, this moisture becomes attached there by crystalline force. Actual melting, however, is not necessary. Slower transfer of molecule by molecule (idiomolecular transfer) accomplishes the result. As these transfers are in response to stress, the result is easing of the stress by yielding. Some granules lose and others gain, and their positions with respect to one another change somewhat. The summation of slight adjustments between innumerable granules is general movement of the mass in the lines of least resistance.

The present studies are entirely in accord with this theory of glacier motion. In many seasons of mountaineering, the writer has walked several hundred miles over scores of glaciers in many different regions. Except where coated with fresh snow, these glaciers were everywhere seen to be aggregates of ice granules. In tiny cliff glaciers the granules were small, in ordinary valley glaciers the size of walnuts was a fair average (Fig. 12); while in some of the large Alaskan glaciers the granules reached 4 or 5 inches in diameter. The unit of glacier ice is the ice crystal or granule, just as the individual unit of a mass of coarse-grained marble is the calcite crystal. In a glacier the larger crystals grow at the expense of the smaller, as was

[1] *A Contribution to the Theory of Glacial Motion*, "The Decennial Publications" (University of Chicago, 1904), Vol. IX, pp. 193–206.

demonstrated long ago in a series of experiments,[1] so that with the forward progress of the ice the crystals become fewer and larger. The ice becomes more and more coarsely granular. This is part of an integrating, crystallizing process, in which the changes among the granules—their growth, changing contacts, partial rotation, etc.—appear to be the fundamental mechanism by which the motion is accomplished.

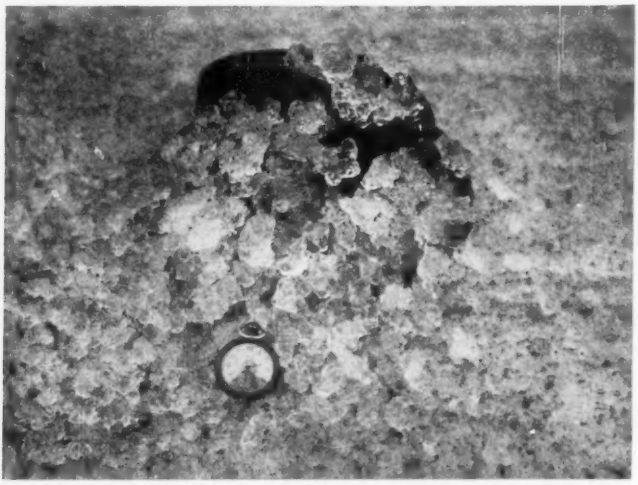

FIG. 12.—Ice granules of Kiwa Glacier, Cariboo Range, British Columbia. Granules piled upon hat to show size.

SMALL-SCALE GENERAL SHEARING

In the lower tongue of a valley glacier, where the thrust from behind and above is great, there is nearly everywhere developed the familiar banded, "parallel," or "ribbon" structure described by many authors, though with much difference of opinion as to its origin and significance. This structure (see Figs. 4, 5, and 6), clearly enough, is of a twofold nature; it is made up in part of definite fractures or planes of slippage and in part of thin bands of relatively transparent, bluish ice essentially free from air bubbles, alternating

[1] By T. C. Chamberlin, C. E. Peet, and E. C. Perisho, "The Decennial Publications" (University of Chicago, 1904), Vol. IX, pp. 193–94.

with thicker bands of more opaque, whitish ice filled with air bubbles. This seems to be a universal glacier-tongue phenomenon. Unequal melting of bubble-filled and bubble-free bands commonly produces a furrowed surface in those portions of the glacier where the structures are steeply inclined or nearly vertical (Fig. 13). Débris accumulates unequally on the ribbed surface and produces the well-known dirt bands.

FIG. 13.—Furrowed surface of right margin of Gorner Glacier, Switzerland

While one large group of glacialists maintains that the blue bands represent the original stratification of the *névé*, the writer's observations lead him to side with the other group which believes them to be of secondary origin. The fact that they are in close parallelism to distinct shear planes, and are everywhere oriented in accordance with the shearing stresses (except in their fading stages, when the older bands are replaced by younger bands related to new stress conditions); that they are best developed where compression and shearing are greatest; that the earlier bands gradually lose their distinctiveness as they move on from the place of their origin; and the fact

that the older bands in many places are seen to have been cut across and displaced along planes which are now newer and sharper blue bands, seem conclusive evidence that they are an oriented pressure phenomenon. For an excellent discussion of this question, the reader is referred to Philipp.[1]

The blue bands and shearing planes seem to be closely related structures. The bands may originate in several ways: (1) water freezing along shearing planes; (2) development of cataclastic structure adjacent to shearing planes, with escape of inclosed air, followed by healing of the fractures by freezing of friction water, or water from surface melting; or (3), since the shearing planes are planes of maximum tangential strain, by an exceptional amount of alternate melting and refreezing concentrated along the planes where yielding most readily takes place. The air bubbles are eliminated, developing bands of bluish, transparent ice; while at the same time the granules in these bands receive more growth than those elsewhere, which is an observed fact.

The strike of these structures on the surface of a glacier tongue invariably parallels approximately, or is concentric with, the curving glacier margin (Fig. 13). Near the sides of a long tongue it is nearly vertical, though in general dipping in toward the middle of the glacier; near the terminus it dips upstream at lower angles. Thus, wherever examined, the dips are prevailingly inward toward the direction from which the thrusting comes, and are in fact a very convenient means of determining one's approximate location on a large glacier in time of fog.

The changing strike and dips are precisely what are required by the mechanics of solid shearing. In the central, axial portion of the ice tongue the major thrust is down the valley, and the ice from behind shears up and over that in front, along planes dipping upstream and striking across the valley. Well back from the terminus, particularly where the lower ice tongue has a gentle gradient and hence there is much flat-lying glacier in front to offer resistance, and where an ice fall behind develops strong thrusting, relief is obtained by up-

[1] H. Philipp, "Geologische Untersuchungen über den Mechanismus der Gletscherbewegung und die Entstehung der Gletschertextur," *Neues Jahrb. für Mineralogie*, Beilage Bd. XLIII (1920), pp. 439–556.

ward movement of the ice mass as well as by forward movement. This is both by granular adjustment and by shearing. Because of the strong upward component of the general ice movement, the angles of whatever shearing planes develop become steeper, and even reach verticality in such portions of the glacier. On the other hand, as the snout of the glacier is approached and the front slope steepens, resistance to the forward thrust of the top portion of the glacier is greatly reduced, both actually and relatively to the resistance offered to the bottom portion. Hence the upper ice shears over that beneath, along planes which become progressively lower in angle toward the end of the glacier. They may even reach horizontality or, if the terminus is located on a considerable slope, may even dip slightly down the slope (Fig. 4).

Along the sides of a glacier tongue the nature of the movement is somewhat different. The middle portion of the ice stream moves more rapidly than the marginal portions, owing to the greater resistance encountered by the latter. Much of this differential motion is of the nature of shear. Shearing planes from differential movement so oriented are essentially vertical and strike in the direction of movement, which is approximately parallel to the glacier sides (Fig. 13). A component of thrust from the middle of the glacier outward modifies dip and strike to a varying extent depending on the location. Since the variation in local movement from place to place is but the appropriate local phase of the movement of the glacier as a whole, so the shearing planes have definitely related trends and dips throughout the ice tongue. Viewed from an adjacent mountain summit, their surface trends (visible in the dirt bands) approximate a parabola in curvature (Fig. 14).

This shearing involves a vast number of thin slices, but the movement along each individual structure plane is slight. This is the second type of movement in a glacier, and the great abundance of shear planes and blue bands indicates that it is an important one. Although the shear-meter was not placed on one of these smaller-type shear planes, where motion is slow and not always in progress, still the results obtained on the major shear plane on the Brenva Glacier would suggest that the shearing on these lesser planes is also by small intermittent slips.

In many long ice tongues, particularly where the glacier has descended through one or more pronounced ice falls, involving changing stress-orientation, later sets of shearing planes are observed to cut across earlier sets of planes (Fig. 15), and later blue bands to cut across earlier blue bands, causing displacement of the severed ends of the older bands. The later blue bands are sharp cut,

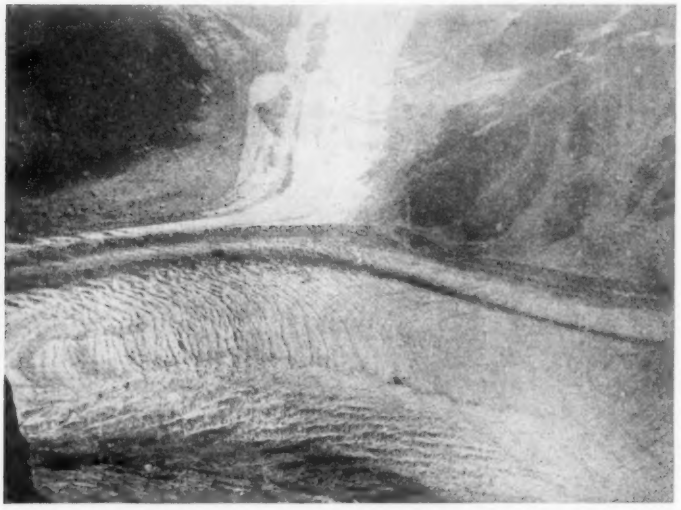

FIG. 14.—Junction of Glacier du Géant and Glacier de Leschaux, viewed from summit of the Aiguille des Grands Charmoz, chain of Mont Blanc. The curving dirt bands are the surface expression of the secondary banded structure. The curves are concave upstream (to the right). The tension crevasses cut across the shearing planes nearly at right angles.

but the older structures are less and less distinct in proportion to their age, owing to the obliterating effect of recrystallization. In places the earlier structures have been sharply folded, the movement between the later slices developing drag folds. The resemblance to sheared metamorphic rocks is close.

DISTINCT THRUST FAULTING

Closely related to the very abundant minor shearing planes are, here and there, a few major planes of slippage which are distinct

thrust faults of considerable displacement. Much greater masses of ice are involved in these displacements, which carry along many smaller slices. This behavior of large masses brings to the fore the brittle, rigid nature of the ice. It was on one such slippage plane that the instrumental records were obtained on the Brenva Glacier which indicated stress accumulation and intermittent slipping. There is

FIG. 15.—Younger set of shearing planes cutting across older shearing planes. Gorner Glacier, Switzerland.

every reason to believe that the shearing along the minor planes is also intermittent, since the difference between the major and minor shearing is more a matter of degree than difference in kind.

BODY MOVEMENT

In addition to these internal differential movements, the glacier slides bodily over the rocks beneath. Individual striae on the bed rock, many feet in length, indicate that the rock fragments which scratched them were held firmly in the basal portion of the ice for considerable lengths of time. This measures in a way the solidity and strength of the basal ice. But at the same time the glacier also

accommodates itself to the configuration of the valley along which it moves. The outlet of a broad *névé* above, in many cases, is only by a narrow ice tongue below, which necessitates great change in the form of the ice mass to permit the passage of the ice into the constricted valley. The glacier, like other rocks, is rigid only up to a certain point; beyond that it yields under stress. But it maintains its crystalline character throughout. Idiomolecular exchange and

FIG. 16.—Older shearing planes and blue bands folded and displaced along newer shearing planes. Kiwa Glacier, Cariboo Range, British Columbia.

adjustment between crystals slowly accomplish the necessary change of form. Where the relations of differential stress to the competency of the ice are of the right sort, shearing upon one another of aggregates of crystals, or slices, co-operates in the adjustment. The more readily these internal changes take place, the more rapidly the body of the glacier slides over the surface beneath.

CONFUSING AUXILIARY MOTIONS

Toward the lower ends of glaciers where the ice is melting and soon to disappear, and also superficially in the whole zone of glacier

wastage, water action of the truly liquid sort is combined with true ice action of the solid sort. Ice melts to its liquid form at one place and is transferred by liquid flow to another place where it refreezes, as is well known. In this way there is some adjustment to stress by passage through the liquid state and there is some migration of the water down the valley. But even in this case it is the refreezing which contributes whatever contribution this water does make to the glacier thrust and well-known grooving power. The gentle percolation of water in the ice and drainage valleyward do not give the powerful rasping effect on the glacier bed, nor do they transport the englacial débris from source to terminal moraine. To avoid these complicating factors, we should really go for a clear-cut case to those parts of the glacier where water is absent, or seek those times when melting is absent. But this encounters other embarrassments and has not yet been attempted.

GENERAL

In summation, there are thus in addition to the transfer, from place to place, of water in the liquid state, four types of movement evident in a glacier:

1. Idiomolecular exchange between granules with yielding and accommodation to stress by changes of position and rotation of individual granules. Analogous to general earth deformation by recrystallization.

2. Solid shearing of aggregates of granules (slices of ice). Movement along the majority of shear planes probably slight. Parallel banded structure and foliation of ice tongue thus developed.

3. Intermittent slip along well-developed thrust faults, involving much larger masses and carrying along many smaller slices.

4. Sliding of the whole body of the glacier over the rock bed beneath.

Of these, the changes in the granules are the most pervasive and fundamental. The shearing and thrust faulting within the glacier, and the movement of the whole over its rocky bed, are larger-unit results of the minute adjustments between a vast number of ice crystals. Moving under the force of gravity, a glacier behaves in essentially the same manner as the rocks of the lithosphere under

the stresses operating in the earth. It would be easy to present in much greater detail this close parallelism in its many different aspects. To those who have been upon glaciers sufficiently to feel thoroughly familiar with the visible phenomena, the moving glacier affords far and away the most concrete illustration of rock deformation available. When perplexed by clashing theories and discordant interpretations of earth deformation, the writer has frequently found that the best remedy for mental wandering in the field of tectonics is to turn to the glacier. Here is a rock of simplest sort actually undergoing deformation before our eyes. Its lessons are invaluable, but unfortunately too few geologists are sufficiently familiar with them.

PALEOZOIC ROCKS OF MISSISSIPPI[1]

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INTRODUCTION

The Paleozoic beds, the oldest rocks outcropping in Mississippi, are confined to the northeast corner of the state. Inasmuch as they are limited on the south and west by overlying Mesozoic sediments of the Mississippi embayment, they constitute the extreme southwestern corner of the Paleozoic area of the eastern half of the United States. They form, therefore, the connecting area between the better-known Paleozoic strata of northeastern United States and the upper Mississippi Valley on the one hand, and Paleozoic beds of the Southwest on the other hand. Their interest, accordingly, reaches beyond the confines of the state.

Not only so, but folding, unconformities, and erosion have brought to view in this small area a wealth of formations heretofore not suspected, or at least but partly recognized. Failure to recognize (1) these lenses or wedges and (2) the horizontal changes in lithology resulted in confusion to the early workers in their *reconnaissance* surveys and led to serious errors in correlation, especially with the beds of adjacent Alabama. As is so commonly the case, these have, unfortunately, been handed down from report to report to the present time.

The writer's introduction to the geology of the Paleozoic beds of Mississippi came late in 1919, when he was engaged in making a commercial survey of that section. Further opportunity to study these most interesting beds was afforded by the Mississippi State Geological Survey, through the courtesy of Dr. E. N. Lowe, state geologist. Under the auspices of the survey, part of the summer of

[1] Abstract of a thesis submitted in partial fulfilment of the requirement for the degree of Doctor of Philosophy from the Massachusetts Institute of Technology. Published with the permission of Dr. E. N. Lowe, state geologist.

1920, part of the summer of 1921, and the whole summer of 1926 were spent in the field.

During the first season Paul Franklin Morse served as an assistant; during the second, T. B. Fatherree and Julian Patrick; during a part of the last, F. E. Vestal, F. N. Geddes, L. H. Shropshire, and E. S. Toney. All were deeply interested and shared most efficiently in the pleasure of determining for the first time the history of these somewhat elusive beds.

More than 120 collections of fossils were made and shipped to the Department of Geology of Massachusetts Institute of Technology, where they were studied during 1926–27 under the most helpful supervision of Professor Hervey W. Shimer. Inasmuch as the report, which was prepared at this institution, may not be published by the Mississippi Geological Survey for some months, it is perhaps desirable to publish a brief abstract of it.

EARLY SURVEYS

The Paleozoic rocks of Mississippi were recognized as such by the second (Harper) state geological survey. In the report, dated 1857, they were referred to "the lower part of the Carboniferous, consisting of a portion of the Mountain (Mississippian) limestone, which extends into Mississippi from the state of Alabama" (p. 34). By means of their fossils, the third (Hilgard) survey placed "the greater portion of the outcrops within the limits of the Warsaw and Keokuk limestones of the Iowa Report" and recognized the possibility "that lower and perhaps even higher groups of the sub-Carboniferous series may hereafter be found to be represented" (1860) (p. 47). Also by means of fossils, which were sent east for identification, the next survey (Crider) recognized Devonian beds of New Scotland age. All the other rocks above the New Scotland and below "the Chert" were likewise referred to the Devonian; some correctly and some incorrectly so. Beginning with "the Chert," the beds, as listed in *Bulletin 283* of the U.S. Geological Survey, 1906 (pp. 7–12), were divided into the Tullahoma (Lauderdale) chert, St. Louis limestone, and Chester, largely after McCalley's Alabama report. In *Bulletin 12* of the state geological survey (1915) all the older beds were named Yellow Creek, and the three younger divisions were called Lauder-

dale chert, Tuscumbia limestone, and Hartselle sandstone (pp. 29, 51–55), as in the Alabama report. Without going into detail, the equivalencies of all these terms are shown in a general way in the subsequent correlation table of the different surveys. In these various reports and on their maps the distribution of the Paleozoic beds were reported to cover parts of Tishomingo, Prentiss, and Itawamba counties.

Arranged in tabular form, the formational terms in common use are the following four:

Mississippian system
- Hartselle sandstone
- Tuscumbia limestone
- Lauderdale chert

Devonian system
- Yellow Creek formation

PRESENT SURVEY

As a result of the present survey the following divisions of the Paleozoic rocks are recognized, and the beds are shown to be confined exclusively to Tishomingo County (Fig. 1). Except for New Scotland, all the formation and member names are new, because of the necessity of introducing new terms for beds heretofore unrecognized, and new terms for those whose limits had unwittingly been shifted until they no longer have a definite meaning.

Mississippian system
- Chester series
  - Forest Grove formation
    - Highland Church sandstone (member)
    - Shale and sandstone
  - Southward Bridge formation
    - Limestone, upper
    - Shale and sandstone
    - Limestone, lower
    - Shale
  - Southward Spring sandstone
  - Southward Pond formation
    - Pond limestone "C"
    - Shale
    - Pond limestone "B"

Shale
Pond limestone "A"
Shale
Allsboro sandstone
Alsobrook formation
Cripple Deer sandstone (member)
Shale
Limestone
Lower (Iowa)series
Iuka formation (chert)
Carmack limestone
Devonian system
Upper series
Whetstone Branch shale
Oriskanian series
Island Hill formation
Helderbergian series
New Scotland limestone

DEVONIAN SYSTEM

The exposed part of the New Scotland, named after the New York formation, is about 40 feet in thickness and consists entirely of massive limestone. The lower half of the formation is filled with beautifully preserved fossils; the upper half is largely barren of fossil forms. In the lower half, *Tentaculites gyracanthus* is, perhaps, the most abundant form, followed closely by *Anoplotheca concava*. Scarcely less common is *Stropheodonta beckii*. *Leptaena rhomboidalis* is very common. Perhaps most striking are the numerous tail shields of *Dalmanites pleuroptyx*. Although the forms in the various lists of the formation in the report proper are not confined to the New Scotland formation and even though its most characteristic fossil, *Spirifer macropleurus*, is not present, nevertheless the formation is referred without question to the New Scotland. This corroborates the conclusions of earlier workers.

The Island Hill formation is named from the beautiful, rounded, isolated hill on Yellow Creek, about 3 miles above its mouth. The formation, which is confined largely to the type locality, consists of a thin basal limestone conglomerate and a few layers of more or less cherty and siliceous limestone, having a total thickness of only 3 feet. Perhaps the most conspicuous feature is the cherty upper layer, from whose weathered surface *Meristella sp.* and *Schuchertella be-*

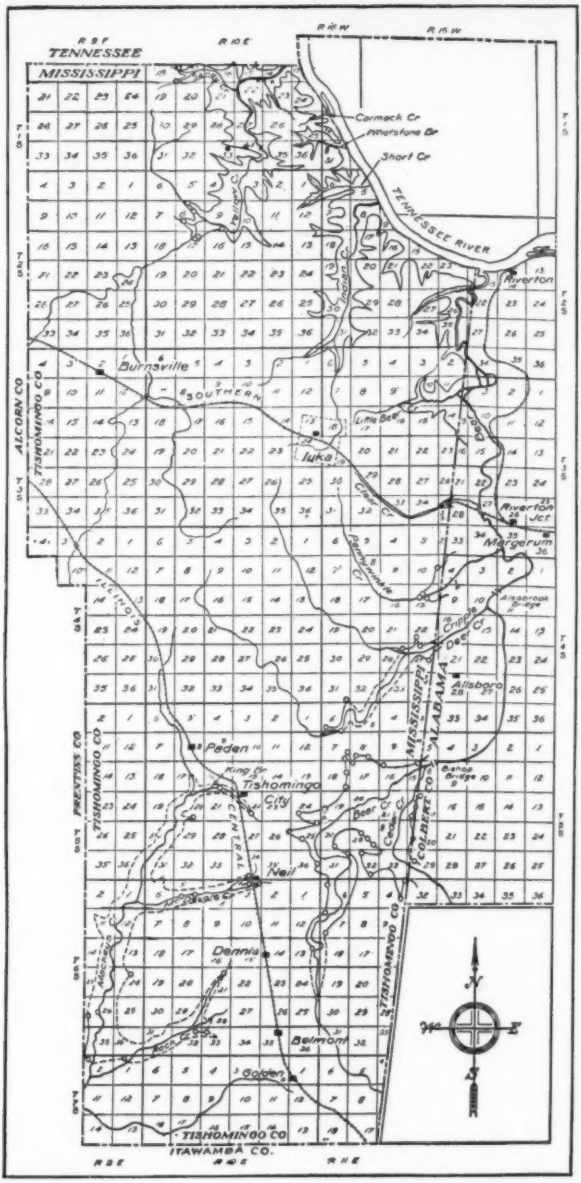

FIG. 1.—Distribution of the Paleozoic rocks in Mississippi, which are confined to the stream courses of Tishomingo County. Beyond the limits of the Iuka quadrangle outcrop stations are shown by means of small circles.

craftensis, as well as other forms, protrude. The formation contains *Meristella lata*, *Stropheodonta magnifica*, *Dalmanites micrurus*, *D. multianulatus*, *D. stemmatus*, and other forms. Though the fauna is closely related to the New Scotland fauna, still the Island Hill forms have evolved notably, some acquiring the sturdy aspect of the hardy Oriskany forms, if, in fact, they had not already completely developed into those forms. In proportion to the size of its shell, *Spirifer cyclopterus* or its descendants had developed huge adductor muscles, so characteristic a feature of the Oriskany Spirifers. Similar had been the development of *Rhipodomella oblata* into *R. musculosa* and of an older *Stropheodonta* into *S. magnifica*. For these reasons the Island Hill formation is referred to the lower Oriskany.

The Whetstone Branch formation, named from the picturesque tributary of the Tennessee, is largely a black shale, though it does contain sandy shales and a few, mostly thin, sandstones. In a number of places the formation is represented only by a rather prominent sandstone layer which has a conglomeratic base and in such places rests unconformably on older formations. In other places typical black shales underlie, and overlie it in such relations as to show that the layer of sandstone is separated from the underlying shales by a contemporaneous erosion surface rather than by a true unconformity. Of course the lowest part of the Whetstone Branch formation at every place in the area rests unconformably on older beds. Likewise it is separated from the overlying beds by a pronounced unconformity. Among other fossils are *Lingula sp.* and *Tentaculites sp.*, the latter form not being known in beds younger than the Devonian. Because of the fossils, and especially because of its unconformable relation to other beds of more definite age, the Whetstone Branch formation is referred to the Devonian. It belongs, therefore, to the lower and greater part of the Chattanooga shale of the type locality. In additional support of this correlation is the work of Morse and Foerste, who showed that the Bedford and Berea formations thin southward from the Ohio River, thus allowing the overlying Sunbury black carbonaceous shale to rest almost directly on the underlying Ohio black carbonaceous shale at Irvine, Kentucky.[1] In the older reports the Ohio shale or the Chattanooga shale of this place con-

[1] W. C. Morse and Aug. F. Foerste, "The Waverly Formations of East-Central Kentucky," *Jour. Geol.*, Vol. XVII (1909), pp. 164–77.

sists, therefore, of the Ohio, Bedford, Berea, and Sunbury formations. Swartz, the younger, has in a similar manner traced the beds still farther south in Tennessee and finds that at Chattanooga nearly the whole of the black shale belongs to the Cleveland (Ohio) and the thin upper part to the Bedford, Berea, and Sunbury formations. He finds also that the black shale of central and western Tennessee is older than Bedford.[1] Thus the work of Morse and Foerste, of Swartz, and of the present writer mutually support one another and the conclusions already reached as to the age of the Whetstone Branch shale.

MISSISSIPPIAN SYSTEM

The Carmack limestone is named from a small stream (containing a 60-foot fall) tributary to the Tennessee River north of Whetstone Branch. The formation is a uniformly thin-bedded brownish or bluish gray limestone which breaks into thin shaly layers on exposure to the elements. It has a maximum thickness of more than 100 feet. As stated previously, it is separated from the underlying formations by a pronounced unconformity. It is also separated from the overlying beds by a great unconformity. Toward the east in Alabama it becomes more cherty and grades into the chert of the Lauderdale formation of that state. From its meager fauna, particularly the association of *Productella* and *Productus* in the absence of a strong Carboniferous phase, the Carmack limestone is known to be Kinderhook, early Mississippian, in age. It has, therefore, been taken from the Devonian and referred to the Mississippian, in which series it is completely included in the Lauderdale formation of the Alabama report. Unlike that formation, however, it does not extend so high. Being separated from the overlying formation by a great unconformity, it is in itself a complete stratigraphic unit.

The Iuka terrane is named from the county seat of Tishomingo County. It has a wide distribution in this county along the Tennessee Valley and its tributaries. In Mississippi it is almost exclusively chert and pulverulent silica, largely the result of limestone leaching and silica replacement. Practically everywhere blocks of chert in great numbers are set free by weathering, thus concealing

[1] Joel H. Swartz, "The Age of the Chattanooga Shale of Tennessee," *Amer. Jour. Science*, Vol. VII (1924), pp. 24–30.

the stratified nature of the beds. At one or two places in Mississippi and at a number of places in Alabama it contains limestone as well as chert. Huge *Orthotetes keokuk* in places in Mississippi and *Lithostrotion canadense* in places in Alabama, as well as other forms, prove respectively the Keokuk and St. Louis age of portions of the Iuka terrane at such localities. In a similar manner other fossils at other places prove the Salem age of a part of it. From all such evidence it is more than probable that the terrane extends almost from the Burlington, through the Keokuk, Warsaw, Salem, and St. Louis, to the Ste Genevieve. Like the other divisions thus far considered, it is separated from the overlying beds by a large unconformity.

The Alsobrook formation takes its name from the Alsobrook homestead and Alsobrook Bridge about which it is excellently exposed. The lower part, varying from a foot or so to 8 or 10 feet in thickness, is a limestone member, which seems more closely related lithologically to the underlying formation than it does to the rest of the formation to which its fossils show it to belong. The upper part of the formation (70 or 80 feet thick) at the type locality is a clay shale save for a thin layer of sandstone near the middle. A short distance south on Cripple Deer Creek the upper third of the formation has changed to a sandstone, the Cripple Deer sandstone member. The sandstone is impregnated with a petroleum residue and is, perhaps, the sandstone which is worked for asphalt in at least one of the quarries farther east in Alabama. In most regions the basal limestone member is filled with *Productus inflatus;* in some places, with *Chonetes chesterensis* as well. In still other localities it contains yet other forms, by all of which its Chester age, rather than its Ste Genevieve age, as maintained by Butts,[1] is established. The remaining portion of the formation is largely barren of fossil forms.

The Allsboro sandstone is named from the small village in Alabama near the Mississippi line. The sandstone is well exposed in many places in the type locality, especially at Bishop Bridge across Bear Creek to the south of the village. Here the formation, 8 feet in thickness, forms a projecting ledge of coarse-grained sandstone. In places it is decidedly contorted, thereby differing from most other

[1] Charles Butts, "The Paleozoic Rocks," *Geol. Survey Alabama Special Report No. 14* (1926), pp. 177–83.

sandstones of the region. In a few localities it contains a little asphaltic material, and it is, perhaps, one of the sandstones worked for asphaltic road material farther toward the east in Alabama. If the fossiliferous block of sandstone at the north end of Southward Pond came from this formation then the sandstone contains a few forms among which *Dielasma shumardanum*, *Productus* (*Echinoconchus*) *alternatus*, and *P. inflatus* are rather robust specimens for a sandy environment.

The Southward Pond formation is exposed around the bluffs of Southward or Cypress Pond, which is perhaps an old meander of Bear Creek. The formation consists of three beds of limestone designated Pond limestone "A," Pond limestone "B," and Pond limestone "C," in the order of their age. Each limestone is underlain and overlain by an interval of shale or shaly limestone. The shale weathers faster than do the limestones, thus causing the limestones to protrude from the surface where the rest of the formation is covered with mantle rock. Especially is this true of the lower limestone, Pond limestone "A." Another conspicuous feature is its oölitic texture; and still another one, at many places, is its asphaltic content. The lower limestone commonly has a thickness of 5–15 feet; the others, a foot or so.

The whole formation of limestones and shales, 80–100 feet in thickness, is extremely fossiliferous, except for Pond limestone "A," whose forms are mostly comminuted beyond the stage of identification. At many places the shallow sea bottom upon which the basal clay and calcareous sediments of the formation accumulated was a veritable flower garden of blastoids and crinoids, among which brachiopods lived in large numbers. The most abundant blastoids were the *Pentremites*, two or three species of which are represented by hundreds of forms; and the most abundant crinoid was *Agassizocrinus dissimilis*. *Zaphrentis spinulosum* and *Composita trinuclea* were also abundant. The conspicuous forms of Pond limestone "B" fauna are the harplike bryozoans, *Lyropora ranosculum*, and the plump medium-sized brachiopod, *Productus lowei*. The uppermost shale is filled with hundreds of large *Chonetes chesterensis*. The fauna on the whole is closely related to the Paint Creek fauna of the Illinois-Kentucky region, which strongly supports the correlation of the Allsboro sandstone with the Bethel sandstone and of the Also-

brook formation with the Renault, and likewise the drawing of the base of the true Chester at the base of the *Productus inflatus* limestone member of the Alsobrook formation.

A part of the Southward Spring sandstone is excellently exposed at Southward Spring, the type locality, where it is 15 feet in thickness. Perhaps twice this amount more nearly represents its complete thickness. It is an impure shaly sandstone, somewhat calcareous, which breaks down rather readily. The peculiar feature of the fauna, collected from blocks of sandstone occupying the position of the Southward Spring sandstone on the north side of Southward Pond, is the presence of *Spirifer* (*Brachythyris*) *chesterensis* (closely related to *S. subcardiiformis*) and of forms referred to *S. suborbicularis*. These forms are largely or exclusively limited to beds no younger, respectively, than the Salem and Keokuk farther to the north. For a sandstone fauna the forms are robust, but the sea bottom was partly calcareous, as is shown by the calcareous material in the sandstone.

The Southward Bridge formation is well exposed in the bluffs of Bear Creek at the type locality, southeast of Southward Spring. The formation consists of a "Lower limestone" and an "Upper limestone," each of which is underlain by a thick interval of shale. It is more than 80 feet in thickness. Near its base is a lens of limestone less than one foot thick which is literally filled with internal molds of a few brachipods. Among these are *Camarotoechia purduei*, *Composita sp.*, and *Liorhynchus carboniferum*. These brachipods, several pelecypods, and still other forms are so closely related to Mississippian faunas in Arkansas as to warrant the conclusion that the two regions were then united, although they are now separated by the sediments of the Mississippi embayment. None of the fossils of "Lower limestone" and of the "Upper limestone" of the same formation merit special attention, except *Spirifer* (*Brachythyris*) *chesterensis*, a form closely related to *S. subcardiiformis*, which in the Mississippi Valley is largely or exclusively restricted to beds no younger than the Salem limestone.

The Forest Grove formation is named after the school which is located on top of the terrane near old Mingo Village and Southward Bridge. Since the top member forms typical sandstone cliffs about Highland Church, located east of Tishomingo City, it is proposed to

name the member after this church. Nowhere is the other member completely exposed. From the nature of the small outcrops here and there and from the manner of slumping of the huge blocks of the overlying Highland Church sandstone it is perfectly reasonable to suppose that practically the whole of the lower member, 90 feet in thickness, is composed of clay and sandy shales and shaly sandstones. The Highland Church sandstone member is massive, 25 feet in thickness, and is a typical cliff-forming sandstone. Contrary to prevalent opinion, some of the sandstones and shales of the Forest Grove formation are fossiliferous. Certain layers are a mass of small gastropods and pelecypods, all, unfortunately, in the form of external and internal impressions, so that specific identification is well-nigh impossible. On Holly Branch of Cedar Creek, however, enough calcareous material has remained to preserve the forms in better condition. Of these, *Deltopecten batesvillensis* is extremely abundant. This pelecypod and other forms show the close relation of this fauna to faunas of the Mississippian beds in Arkansas, on the other side of the embayment. Otherwise the Forest Grove faunas warrant no further consideration except to note their strong Chester development.

SUMMARY

Briefly, the results of the present survey may be summarized in the form of two correlation tables and a few paragraphs. In the first table the various formational names of the Mississippi (and adjacent Alabama) region are correlated in so far as this can be done in a table. In the second table a correlation of the beds of more widely separated areas has been attempted.

The Paleozoic rocks in Mississippi were originally referred to the Mountain limestone, the lower part of the Carboniferous system. Because of their fossil content, they were next placed within the limits of the Warsaw and Keokuk limestones of the Iowa reports. Still later collections of fossils showed the lowest part of the group to be New Scotland (Devonian) in age, while the remaining portion below "the Chert" was also referred to the Devonian, and the upper divisions were referred to the Tullahoma (Lauderdale) chert, the St. Louis limestone, and the Chester series, largely according to the Alabama Geological Survey reports. Finally the New Scotland limestone and all the beds lying below "the Chert" were named the Yel-

low Creek formation, and the other beds were referred directly to the Lauderdale (Keokuk) chert, the Tuscumbia (St. Louis) limestone, and the Hartselle formation of Alabama.

The present researches have shown (1) that there were serious errors of correlation between the beds of the adjacent parts of the two states and (2) that the Yellow Creek is not a single stratigraphic unit, but that the terrane consists of several formations separated by marked stratigraphic unconformities and paleontologic breaks.

TABLE I

CORRELATION TABLE OF THE DEVONIAN AND MISSISSIPPIAN FORMATIONS RECOGNIZED BY THE DIFFERENT SURVEYS OF THE NORTHEAST PART OF THE STATE

Morse 1927	Lowe 1915	Crider 1906	McCalley 1896 (Alabama)	Hilgard 1860	Harper 1857
Forest Grove Southward Bridge Southward Spring Southward Pond Ailsboro Alsobrook	Hartselle	Chester	Hartselle	Warsaw	Mountain limestone
Iuka	Tuscumbia Lauderdale	St. Louis Tullahoma	Tuscumbia		
Carmack			Lauderdale		
Whetstone Branch Island Hill New Scotland	Yellow Cr.	New Scotland	Black shale	Keokuk	

Furthermore, these formations belong to two great systems, the Devonian and Mississippian, rather than to one only. These formations, new to the science of the state, have been given new names: the Island Hill formation, the Whetstone Branch formation, and the Carmack limestone.

The fauna of the Island Hill formation has been determined to be early Oriskany in age. The Whetstone Branch formation is none other than the "Black shale," the Chattanooga shale of the south, the Ohio shale of the north, over whose Devonian or Mississippian age a controversy has raged for years. Assisted by Dr. Foerste, the writer showed that the "Black shale" at Irvine, Kentucky, consists of the Ohio black carbonaceous shale (Devonian) and the Sunbury black carbonaceous shale separated by a few inches of clayey shale representing the Bedford and Berea (Mississippian), due to the

thinning of these two formations southward. With this as a basis, Swartz showed that practically the same condition obtains at Chattanooga, the type locality, and yet the storm continues. The present work shows that the Whetstone Branch shales are separated from the overlying Carmack limestone, early Kinderhookian (Mississippian) in age, by a profound unconformity, and that the Whetstone Branch shale must therefore be Devonian rather than Mississippian in age. The work has thus confirmed the earlier conclu-

TABLE II

CORRELATION TABLE OF THE DEVONIAN AND MISSISSIPPIAN FORMATIONS OF THE DIFFERENT STATES

Standard Weller 1921	Mississippi Morse 1927	Alabama McCalley 1896
Hardinsburg Golconda Cypress Paint Creek Bethel Renault	Forest Grove Southward Bridge Southward Spring Southward Pond Allsboro Alsobrook	Hartselle
Ste Genevieve St. Louis Salem Warsaw Keokuk Burlington	? Iuka	? Tuscumbia (St. Louis)
Kinderhook Chattanooga	Carmack Whetstone Branch	Lauderdale (Keokuk) Black shale
Oriskany New Scotland	Island Hill New Scotland	

sions that the Chattanooga shale at Irvine and at the type locality is in large part Devonian and in small part Mississippian. As just stated, the Carmack limestone has been determined to be Kinderhook in age.

The thin upper part of the old Tuscumbia formation and the thick series of sandstones, shales, and limestones long known as the Hartselle have been found to consist of a series of formations. These have, of necessity, been given new names: the Alsobrook, Allsboro, Southward Pond, Southward Spring, Southward Bridge, and Forest Grove. All these are Chester in age, and correlate approximately with beds occupying the same positions in the Chester series of the Illinois-Kentucky region.

A RECONNAISSANCE OF THE WASATCH FRONT BETWEEN ALPINE AND AMERICAN FORK CANYONS, UTAH

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ABSTRACT

During the Laramide revolution compressive stresses acting tangentially from the southwest produced the major structure. Thrust faulting was associated with the folding, but normal faulting was caused by later vertical stresses exerted by the Cottonwood igneous intrusion. These normal faults occurred along planes of weakness already initiated by the previous folding.

INTRODUCTION

Lying mostly in north central Utah, the Wasatch Mountains form a narrow range extending north from Mount Nebo, Utah, for a distance of approximately 160 miles to McCammon, Idaho. Having been cut off on their western front by the Wasatch Fault, they mark abruptly the eastern border of the Great Basin.

The area mapped extends 5 miles north from the mouth of American Fork Canyon along the front of the range; thence approximately 7 miles easterly into the very heart of the Wasatch. It is situated 25 miles south of Salt Lake City and immediately east of the little town of Alpine.

Due to the complex manner in which the rock strata have been broken and shifted by faulting, no attempt was made to map all of the numerous faults, for the exceedingly rugged character of the topography prohibited such an undertaking in the time devoted to the work. Consequently, the reconnaissance map and accompanying structure sections are designed to show only the salient structural features. However, in order to give some detail of the characteristic local folding and faulting, a plane-table traverse was made of Tank Canyon, a north branching tributary of American Fork Canyon, which cuts almost directly across the structure so that an excellent section is exposed.

STRATIGRAPHY

The stratigraphy of the area corresponds essentially to that of the Cottonwood-Park City and American Fork districts which are described in some detail by Butler, Loughlin, and Calkins.[1]

Because this reconnaissance was undertaken primarily to study the structural geology, no special investigation was made of the stratigraphy. However, during the field work, some additional stratigraphic information was obtained, and the following condensed outline represents the formations which were recognized during the mapping:

QUATERNARY

Recent: River gravels and alluvium
Pleistocene: River gravels and glacial deposits

TERTIARY

Eocene: Wasatch conglomerate, coarse, pink to red

PALEOZOIC

Pennsylvanian: Weber quartzite, fine grained, light gray to light brown quartzites interbedded with limestones
Lower Pennsylvanian to Cambrian (Ordovician and Silurian missing): Undifferentiated limestones
Cambrian: Ophir shales, interbedded gray-green shales and argillaceous limestones
Tintic quartzites, medium grained, pink to light red
Basal conglomerate
Pre-Cambrian: Quartzite, white to very light pink, of coarse grain and containing stringers of conglomerate along bedding planes
Tillite, dark brown, containing quartzite pebbles and bowlders, also sandstone lenses

IGNEOUS

Post-Jurassic: Cottonwood granite, coarse grain, contains biotite, hornblende, orthoclase, and cloudy quartz

Of interest in connection with the Tintic formation is an outcrop of conglomerate, discovered on the west slope of the section, beneath about 800 feet of the quartzite. It is 40 feet thick and composed chiefly of rounded quartzite pebbles and bowlders which reach a maximum diameter of 8 inches, decreasing in size toward the upper part until the formation grades into the true Tintic quartzite. Al-

[1] B. S. Butler, G. F. Loughlin, and F. C. Calkins, *U.S. Geol. Survey, Prof. Paper 111*, pp. 233–40.

though no angular discordance was detected, this member is correlated with a conglomerate in Big Cottonwood Canyon considered by Blackwelder[1] as being the basal conglomerate of the Cambrian system.

REFLECTION OF STRUCTURE BY THE TOPOGRAPHY

Briefly, the structure of the area consists of two anticlinal folds with a connecting syncline which strike northwest and pitch to the southeast. On Boxelder Peak, which rises abruptly on all sides, the area reaches its maximum elevation of 11,080 feet. Here there is a definite relation between the structure and the topography, for the top of Boxelder Peak is also the highest point on the crest of the north anticline.

Throughout the district the formations are well exposed, due to the many deep gorges that have been carved by the streams, which in many cases are adjusted to the structure. For example, the canyons of the streams flowing east into Deer Creek, as well as the headwaters of the latter, are typical strike canyons, in the walls of which the beds in some places stand almost perpendicularly.

American Fork Creek, the master stream, draining about two-thirds of the area, is an outstanding exception to the well-adjusted drainage system characteristic of the region. Flowing swiftly with an average fall of 1 foot in 20, it has cut its canyon obliquely across the structure, regardless of the resistant rocks. Even the Tintic quartzites have been worn through without deflecting the course of this stream.

As American Fork Creek cut its channel, drainage into it from the north was established. These south-flowing tributaries of the master stream—Tank Canyon and its neighbor immediately to the west—cut almost directly across the structure, and on their precipitous walls north-south-structure sections are clearly exposed.

On the west slope of the district, the streams are flowing parallel to the strike of the rocks, a natural result of a drainage established on the face of the Wasatch Fault, which here cuts across the structure. The position of this fault on the map (Fig. 1) is only approximately shown because of the lack of exposures in this area.

[1] Eliot Blackwelder, "New Light on the Geology of the Wasatch Mountains," *Bull. Geol. Soc. Amer.*, Vol. XXI (1910), pp. 520–23.

However, evidence of this eroded fault scarp is clearly reflected in the topography of this quadrangle in the following manner: (1) by the abrupt rise of the range above the valley floor, with a short

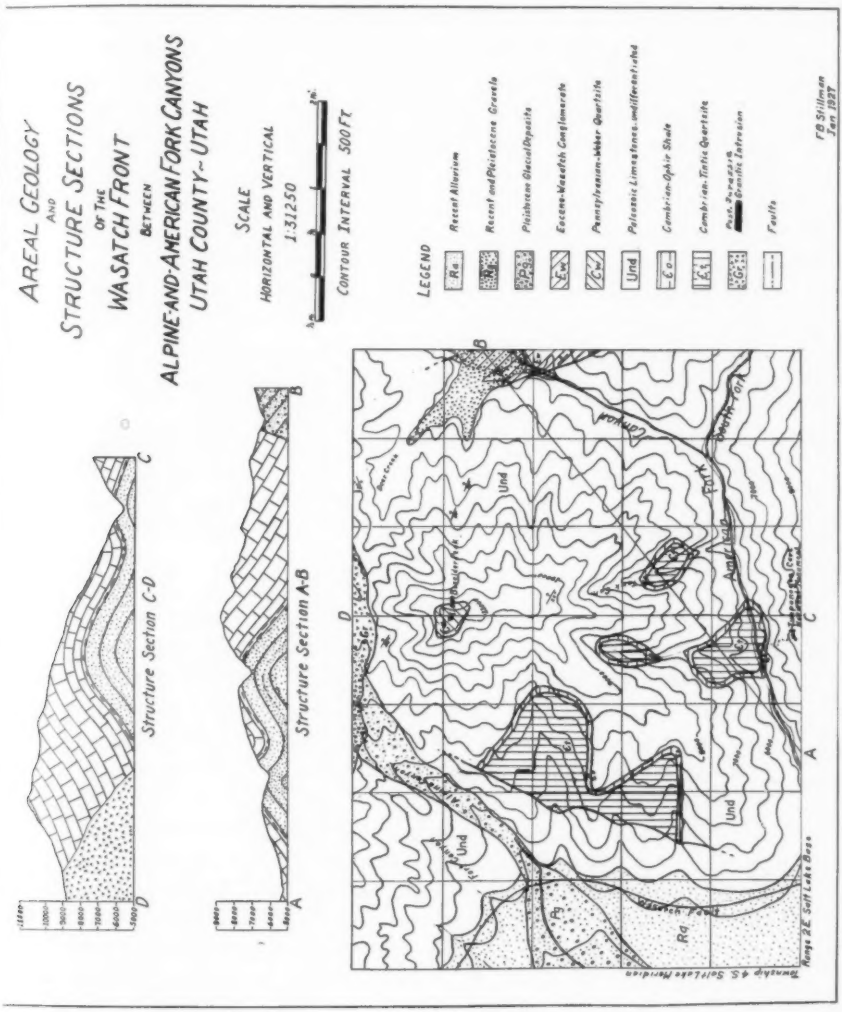

FIG. 1

piedmont slope; (2) by the sharply defined boundary of the mountain front; (3) by the steepness of the front which is from 30° to 35°; and (4) by the location of high mountain peaks on the extreme front of the range.

STRUCTURAL GEOLOGY

It is generally recognized by geologists that the present structure of the Wasatch Mountains is largely the product of two periods of uplift. The first major deformation was caused by lateral compressive stresses that were active over the entire Cordilleran region during the Laramide revolution. This disturbance in the Wasatch is characterized by a rather intense folding of the strata; and the resulting structures in general have a north-south trend, although local folds deviate materially from this general direction. The folding seems to have been accompanied by thrust faulting.

Following the Laramide revolution, an erosion interval set in, during which the uplifted area was partially peneplained; and upon this surface Eocene sediments were deposited.

The second deformation of the Wasatch Range was caused by a vertical uplift on the east side of the Wasatch Fault, which occurred after the close of the Eocene.

FOLDING

The effect of folding in the area under discussion is expressed by two parallel, asymmetrical anticlines and a connecting syncline, which strike N. 55° W. and pitch about 15° to the southeast. In both anticlines the steeper dips are toward the north, the north flank of the north anticline dipping from 30° to 50° toward the granite stock, while the south flank of the south anticline decreases to a very gentle dip as it passes southward. The distance between the crests of the anticlines is approximately $1\frac{1}{2}$ miles, the north fold having the greater inflection length.

In the Paleozoic limestones the axial plane of the north anticline dips 55° to the southwest in contrast to a dip of 75° in the underlying Tintic quartzites. This evidence clearly indicates that the axial plane is folded over to the northeast and that there has been an overriding of the quartzites by the relatively incompetent limestones.

As would be expected, deformation in the massive quartzites,

which form the cores of the folds, is characteristically that of the competent, concentric, open type, showing no thickening or thinning. The overlying limestones, on the contrary, exhibit a relatively incompetent failure, as illustrated in Figure 2. In these limestones there is a pronounced thickening of the beds toward the crests of the anticlines, and a thinning along the flanks. Also, in the limestones, the departure from symmetrical folding is greater than in the underlying more competent quartzites, and drag folding is a common

FIG. 2.—Folding in incompetent limestones

feature of the more thinly bedded members, an example of which is illustrated in Figure 3.

Considering the asymmetrical type of folding, with the steeper dips on the northeast flanks of the anticlines, and the fact that the axial plane of the north anticline has been folded over to the northeast, it seems logical to suppose that the force which produced the deformation was a lateral, compressive stress, acting tangentially from the southwest. Moreover, the small inflection lengths of these folds would tend to minimize the possibility of ascribing the deformation to a vertical stress. Such a vertical stress, were it localized in as small an area as the one under discussion, and beneath the then existing great overburden of limestones and quartzites, would undoubtedly have produced much larger and broader structures.

FAULTING

Both normal and reverse faults are prominent in the area, the normal being far more numerous than the reverse type. In most cases both types of faults have high angles of dip, usually exceeding 50°.

The normal faults, with dips varying from 60° to 85°, may be separated into two groups: those striking approximately north-south, oblique to the folded structure and parallel to the long axis

FIG. 3.—Drag folding in thin-bedded limestones

of the Wasatch Mountains; and those striking northwest, parallel to the folding.

All of the reverse faults observed follow the strike of the folds and dip to the southwest.

Considering the faulting in more detail, the Wasatch Fault, striking with minor curves in a north-south direction, is the major displacement of the district and one of the outstanding faults of the well-known Basin Range type. It has a westward dip of 70° and a displacement of at least 5,000 feet, as recently shown by Schneider[1] and later confirmed by Pack.[2] A similar fault in the west part of the area and east of Wasatch Fault also has a north-south trend.

The faults in American Fork Canyon, forming a *Graben* of

[1] Hyrum Schneider, "A Discussion of Certain Geologic Features of the Wasatch Mountains," *Jour. of Geol.*, Vol. XXIII (1925), No. 1, pp. 32, 48.

[2] F. J. Pack, "New Discoveries Relating to the Wasatch Fault," *Amer. Jour. of Sci.*, No. 65 (May, 1926).

Eocene conglomerate, as shown in Figure 1, strike in a general north-south direction; and, although no measurements of the displacements by these faults were obtainable, the formations affected suggest a throw of several hundred feet. From the foregoing evidence it is concluded that the faults having a general north-south trend are of the Basin Range type and of post-Eocene age. They doubtless were formed at the same general time as the Wasatch Fault and by the same stresses.

In the Tank Canyon section (Fig. 4), which is located about 3 miles south of the granite stock, there is a fault zone showing displacement by both normal and reverse faults. All of these strike parallel to the folds and dip to the southwest, but most of the reverse faults show minor displacements compared with those of the normal type. It is thought that the reverse faults were coincident with the Laramide folding, being caused by lateral compressive stresses from the southwest.

The normal faults of the Tank Canyon section, which represent the second type of normal faulting previously mentioned, are of unusual interest, for they have the same general trend and dip as the thrust faults with which they are associated. Also, the total displacement by these normal faults exceeds that of the thrust faults. Figure 5 shows the pre-Cambrian quartzite faulted down against the tillite, the resistant quartzite standing out boldly as a perfect example of an obsequent fault-line scarp. These normal faults paralleling the folds are decidedly in contrast to the usual north-south normal faults, and the question naturally arises as to their probable cause and age. Their restricted occurrence and proximity to the igneous rocks suggest a close genetic relation to the granite intrusion.

RELATION OF THE COTTONWOOD GRANITE INTRUSION TO THE STRUCTURE

In the first study of the Cottonwood granite, King and Emmons[1] regarded this intrusion as pre-Cambrian; but later Emmons[2] concluded that it was post-Jurassic.

[1] Clarence King and S. F. Emmons, *U.S. Geol. Explor. of the 40th Parallel* (1878), p. 48.

[2] S. F. Emmons, "The Little Cottonwood Granite Body of the Wasatch Mountains," *Amer. Jour. of Sci.*, Vol. IV, No. 16 (1903), pp. 139–47.

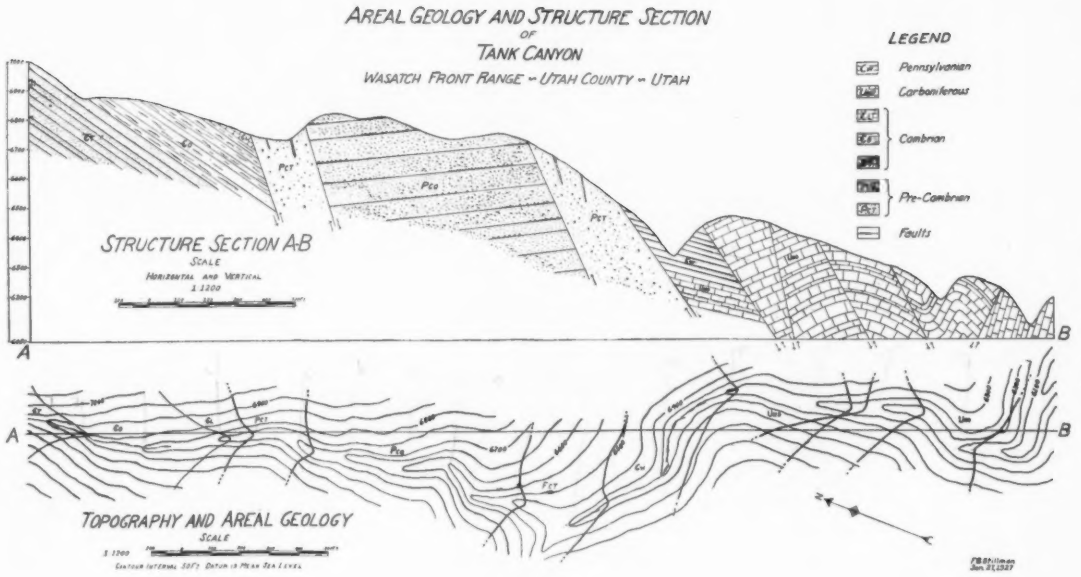
AREAL GEOLOGY AND STRUCTURE SECTION
OF
TANK CANYON
WASATCH FRONT RANGE – UTAH COUNTY – UTAH
LEGEND
Pennsylvanian
Carboniferous
Cambrian
Pre-Cambrian
Faults
STRUCTURE SECTION A-B
SCALE
HORIZONTAL AND VERTICAL
1:1200
A
B
TOPOGRAPHY AND AREAL GEOLOGY
SCALE
1:1200
CONTOUR INTERVAL 50 FT. DATUM IS MEAN SEA LEVEL
F.B.Stillman
Jan. 31, 1927

FIG. 4

However, as the result of a recent, rather extensive study of various sections of the Wasatch Mountains and adjacent areas, Beeson[1] believes the granite to be Eocene. As supporting evidence, he points out that the western terminus of the Uintah Mountains, which he considers to be the result of doming by an igneous intrusion in the Eocene, meets the Wasatch Range almost at a right

FIG. 5.—Obsequent fault-line scarp by normal faulting, down-thrown to the right

angle, the intersection being approximately at the igneous intrusion in the Wasatch. This gives the appearance of a continuation of the effect of the Uintah uplift through the Cottonwood stock, which, if true, would place the time of intrusion in the Eocene.

Although in this district no direct evidence is available which might be used to definitely determine the age of the Cottonwood granite, the following suggestive field data would appear to warrant a somewhat earlier time of intrusion than Upper Eocene.

[1] J. J. Beeson, "Mining Districts and Their Relation to Structural Geology," *Mining and Metallurgy*, September, 1925.

The youngest rocks in contact with the granite are Carboniferous. Field evidence shows that throughout the entire length of Alpine Canyon, the Paleozoic rocks dip toward the granite at angles of from 30° to 35°, the relation of these beds to the stock being illustrated in Figure 2. In this photograph the right-hand flank of the fold is dipping north toward the granite. Less than 1 mile to the east the beds dip away from it at an angle of 30°. On the north side of the stock is exposed a large section of the old pre-Cambrian rocks, which roughly conform to the contact and dip steeply to the north; but on the south side of the granite the same rocks are deeply buried and dip either toward or away from the stock at various angles.

If the Cottonwood granite is a continuation of the Uintah uplift and the Uintah uplift is a dome resulting from an igneous intrusion in the Eocene after Laramide folding had ceased, it seems unlikely that so many beds should dip steeply toward the intrusion. Moreover, according to the present conception of the causes of diastrophism and their relation to vulcanism, it seems probable that the upwelling of the magma which formed the granite stock might have come about through the relief of stress in the deeper zone underlying this area, immediately following the arching of the overlying strata.

Regardless of the fact that the time of intrusion cannot be conclusively proven, it is thought that the unusual normal faults, previously mentioned, have a direct bearing on the problem. Their relation to the folding is reflected by a parallelism to the strike of the folds and by the southwest dip of the fault planes. Such a close similarity to the strike and dip of the associated thrust faults, which are undoubtedly connected with the folding, was probably the result of failure along planes of weakness already initiated. Thus, immediately following the relief of compression, normal faulting naturally resulted from the vertical stress exerted by the intruding magma, the strike and dip being controlled by strains produced during the folding.

If the foregoing interpretation of the field evidence is correct, it then follows that the intrusion occurred immediately after Laramide folding rather than during Eocene time.

SUMMARY

The major structure consists essentially of two anticlinal folds with a connecting syncline, which strike approximately N. 55° W. and pitch about 15° southeast. This deformation resulted from lateral compressive stresses, acting tangentially from a south-west direction, during the Laramide revolution. Deformation has apparently been controlled by the older quartzite formations, a feature noted by Schneider[1] in the section east of Salt Lake City. Also, these older rocks show open broad folding, in contrast to the relatively incompetent, overlying limestones which are closely crumpled.

There are three types and periods of faulting: (1) thrust faulting associated with folding during the Laramide revolution; (2) normal faulting, due to a vertical relief of stress along planes of weakness already produced by this folding (the vertical stress was probably exerted by the Cottonwood igneous intrusion, either coincident with or immediately following the initial folding); (3) north-south normal faulting of the Basin Range type, of post-Eocene age.

In closing, the writer takes pleasure in acknowledging advice received in the field from Professor H. Schneider, of the University of Utah, who also suggested the problem, and from Professor C. M. Nevin, of Cornell University, for helpful criticisms during the preparation of this paper.

[1] Hyrum Schneider, *op. cit.*, p. 48.

THE ASOTIN CRATERS OF THE COLUMBIA RIVER BASALT

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ABSTRACT

A series of vents in the Columbia River basalt are exposed along the Snake River at the Washington-Idaho boundary. These furnish proof of explosive origin. Evidence is offered to prove that this activity has been due to the contact at depth of basaltic fissure eruptions with water-saturated gravels. With the explosions, the dissolved steam resulted in the local formation of an artificial pumice, which appears to have been accompanied by a partial volatilization of the iron content.

INTRODUCTION

The Columbia River basalt has long been considered to have been derived from fissure eruptions. In some localities dikes are relatively common, but as a rule the feeders are not apparent until erosion has removed the actual point of extrusion. In consequence, the details of the mechanism have seldom been determined. The individual fissure, however, is generally conceded to have extruded great quantities of lava with little or no explosive action. With the cessation of extrusion the thin body would have rapidly solidified.

The Snake River, however, has revealed a series of vents along the Washington-Idaho boundary that were undoubtedly accompanied by great explosive activity. They are located close to the eastern border[1] of the great basaltic fields, but even here the flows are at least 2,000 feet in thickness. The older mountain masses that rise with steep contacts through the surrounding flows testify to the rugged topography on which the basalts were extruded. The fertile Lewiston Basin, in which the vents occur, is a broad asymmetrical syncline with an approximate east-west axis. It is bounded both on the south and southeast by old mountain masses from which the flows dip northward at low angles, reaching their lowest point in a

[1] I. C. Russell, "Geology and Water Resources of Nez Perce County, Idaho," *U.S. Geol. Survey Water Supply Paper 53* (1901), pp. 55–60.

distance of about 15 miles near the junction of the Snake and the Clearwater (Fig. 1). Just north of this the basalt rises steeply to the

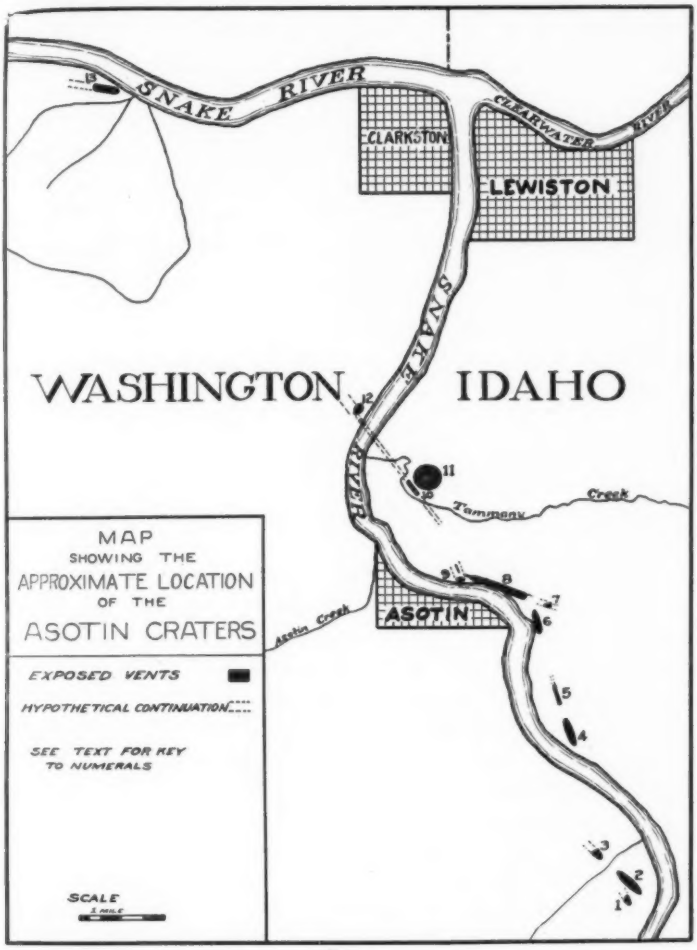

FIG. 1

Union Plateau some 2,000 feet above. The canyon formed by the Snake, as it flows northward through the basin, gradually dies out,

only to be renewed again as the river swings to the west before cutting through the Union Plateau.

The exposures are confined to a zone about 10 miles long and scarcely more than a mile wide, traversing the western portion of the Lewiston Basin in a northwesterly direction. The name chosen by the author is based on the proximity of the main feeders to the town of Asotin, Washington. Adjacent to this town the vents lie approximately parallel to the river. The numerous small tributaries cutting the steep canyon walls, which here rise about 700–1,000 feet above the river, furnish a number of cross-sections. The excellence of these exposures provides definite evidence regarding the factors that apparently produced their many peculiarities.

PREDOMINANT CHARACTERISTICS

The activity of the vents was almost contemporaneous. In spite of a similarity in mechanism the results vary considerably in complexity. The gradual accumulation of data permits a relatively complete interpretation of their different phases. A statement of the predominant characteristics of this interpretation would add to the clarity of the subsequent description of the particular phase represented by each vent.

The elongate outline of the vents, as well as their alignment into several main systems, indicates a strong relationship to true fissures, but their rounded ends and widely flaring mouths, cross-cutting the earlier horizontal flows, justify their classification as craters, although of a type that appears to have no direct analogy to any previously described. The brecciation accompanying the clean-cut beveling of these earlier flows requires an explosive mechanism. The inclined surface thus formed is almost invariably overlain by a fine partially altered glass breccia on which rests the chilled margin of the central filling. Usually the crater filling exhibits columnar jointing normal to the margin.

The pyroclastics.—The origin of the vast quantities of glass pyroclastics associated with the vents is of especial importance. These breccias are formed largely by the hydration of coarse particles of sideromelan, which is a type of basaltic glass distinguished from tachylite by the absence of the iron ores. Although megascopically

black and vitreous, in thin section the glass is transparent and of a pale yellowish to brownish green. Exceptionally rapid chilling is considered to be essential for the retention of the iron oxide in solution. The previous descriptions of sideromelan have been confined to basaltic tuffs, which usually have been associated with aqueous chilling or, as in Iceland, to subglacial extrusion.

This glass is usually hydrated to palagonite, a yellow colloidal mineraloid. From his recent studies[1] on the basalts of Iceland M. A. Peacock has determined two varieties of this substance: One is a gel which was thought to result usually at relatively low temperatures and high pressure; the other is an obscurely birefracting fibro-palagonite which he found associated largely with hot springs. Both varieties are present intermingled at the Asotin Craters, although the gel appeared to be far more common. The hydration has been shown to be accompanied by a partial loss of lime and soda. This fact explains the irregular patches of calcium carbonate which at times form the cementing material.

Evidence on the mode of chilling.—In the present instance these pyroclastics have undoubtedly been formed at depth and then extruded in the form of sand flows. Masses of this material imbedded in the vents never reached the surface. Where it is deposited on the flaring crater walls it exhibits pseudo-bedding due to lines of flowage. An examination of this flowage furnishes definite evidence of upward movement.

Evidence is furnished on the mode of this subterranean chilling by the quantity of coarse waterworn sediments intermixed with the pyroclastics. Although some of the pebbles show no perceptible effect from heat, often they are highly fractured, spalled, and iron stained. Where calcination has been greatest, only the most siliceous survive. Granitic types often crumble to pieces in the hand. Presumably this association of sediments and palagonite is due to the contact of basaltic dikes with water-saturated gravels underlying the earlier flows of the series. The effect on the lava would be similar to that which takes place in the granulation of slag. In fact, aside from being more finely vesicular, the unaltered sideromelan is almost

[1] Martin A. Peacock, "The Petrology of Iceland," *Trans. Royal Soc. Edinburgh*, Vol. LV, Part I, No. 3, pp. 52–76.

identical in appearance to quenched slag. The superheated steam generated by this chilling would undoubtedly have been a rapid agent in the alteration of these glass particles.

Additional proof of the chilling of the lava on its contact with the gravels was furnished by a quartz grain about .3 cm. in diameter found imbedded in a large fragment of sideromelan in a fairly coarse breccia. More conclusive evidence of the underlying sediments is furnished by the gravels imbedded in a vesicular dike exposed on the western wall of the Snake River Canyon at about a mile south of the margin of the map. This dike represented a late intrusion whose point of extrusion has been removed by erosion. From the absence of evidence of explosion, the gravels in this instance must have lacked the saturation encountered by the earlier larger fissures.

The formation of the craters.—The expansion of the water vapor generated by this subterranean chilling has formed, at intervals along the fissures, elongate diatremes with flaring mouths cutting through the relatively superficial cap composed of the earlier flows. These phreatic explosions probably were accompanied by the irregular injection of basaltic apophyses into the disrupted gravels. These injections would have sealed the margin of the still molten column, which would have risen upward in the open vent carrying with it the glassy pyroclastics and their associated sediments, together with the surviving material left by the original explosion.

The final stage of extrusion of this glass breccia varies at different craters. In places it still caps the vent where the column of lava lacked sufficient force to eject the yielding mass. In some places it was extruded and deposited as a sand flow on the lip of the crater. More commonly it survives only on the flaring walls. In this case it probably was largely carried away intermingled with the surface lava of a subsequent flow.

The relatively low temperature of the mass is shown by the layer of sideromelan that usually coats the lava that injects it. In fact the brecciation of glassy apophyses undoubtedly contributes to the bulk of the pyroclastics. No tendency toward palagonitization was observed in this later sideromelan.

Basaltic bowlder beds.—Low on the margin of these craters coarse basaltic bowlders are often imbedded in palagonite. Some of the smaller individuals are undoubtedly waterworn and have an origin

similar to that of the assorted siliceous ones with which they are associated. Some are from the brecciation of the basaltic caps. Some, however, are considered by the author to have been derived from pillow lava. As the column of lava rose under the cap of palagonite its steam concentration might well be expected to have resulted in the formation of pillow lava in the upper part. The individual pillows might then be separated by explosion or mere movement and incorporated in the overlying pyroclastics. Then, with extrusion, this local phase would be deposited on the flaring margin. The bowlders often have an undulating contour which suggests a primary surface, yet in thin section they show no chilling. This fact, as well as their common uniformity in size and composition, substantiates the hypothesis.

White tuffs.—In addition a pale-gray to white tuffaceous material occurs locally in the craters. This is composed largely of minutely shredded lava with vesicles ranging from 0.004 to 0.08 mm. in diameter. This pumiceous material has been somewhat altered to a fibrous hydration product. These white tuffs, which in places contain small fragments of sideromelan, have been observed only at the margins of the actual vents. There they have been associated with sediments and overlain by typical far coarser palagonitic breccias, with which they are partially intermixed. From their occurrence they appear to accompany only an explosive phase.

Steam, above its critical temperature, has been shown to dissolve readily in glass silicates. Far below the melting point of the dry silicate it renders the solution fluid.[1] At the top of the column of basalt, immediately prior to the explosion, the volatile content, owing to the water, would have been greatly increased. With release of pressure accompanying the explosion, this uppermost superficial layer of lava would have frothed in a manner characteristic of the more acidic volcanics. This fact has been demonstrated experimentally with olivine and water at a pressure of ten tons to the square inch.[2]

[1] George W. Morey, "New Crystalline Silicates of Potassium and Sodium. Their Preparation and General Properties," *Jour. Amer. Chem. Soc.*, Vol. XXXVI (1914), No. 2, pp. 225–27.

[2] Charles A. Parsons, "Researches at High Temperatures and Pressures," *Nature*, Vol. CXIV (1920), p. 109.

Differentiation.—The normal rock of these vents is a basic augite-olivine-basalt. Labradorite and augite predominate in an intersertal texture, while larger grains of olivine and dendritic magnetite form common accessories. The sharp contrast between this basic rock and the acidic-looking white tuffs demanded a series of chemical determinations of the relative silica content of the associated phases. The results of these analyses, which are given in Table I, indicate a progressive increase in the silica toward the top of the column of basalt which once filled the vents. In the hope of explaining this relationship the iron content was also determined.

TABLE I

	SiO_2	Fe_2O_3
1	45.30	11.43
2	47.69	11.18
3	49.91	12.01
4	48.86	11.65
5	49.63	10.17
6	53.94	5.05

1. Basalt welling into a flow at crater (7).
2. Top of static phase of probably same vent at (8).
3. Sideromelan in white tuff at (8).
4. Basaltic crater-filling at (13).
5. Vesicular sideromelan in white tuff at (13).
6. White tuff (water 10.18 %) at (13).

All analyses are calculated on the anhydrous material. Ferric oxide represents the total iron content. A. L. Knisely, analyst.

In specimen 2 a fragment of plagioclase varying from acidic andesine to basic oligoclase was observed. This fragment necessitates a foreign origin that may well be due to the disintegration of the unconsolidated sediments encountered by the rising lava. The concentration of this foreign matter would have been aided by its own relatively light specific gravity. The accumulation of both the inherent and the exotic volatile constituents in the upper part of the basaltic column would have stimulated the assimilation of the fine particles. In a static vent gravitational separation of the earlier crystallizing basic minerals may be of minor importance. These factors may well explain the differentiation in the first three specimens.

The field relationship of the last three is far more definite. These come from closely associated phases that should have accompanied an initial explosion. The analyses indicate that the relative increase in the silica is due to a corresponding loss of iron. The freshness of the specimens and of the associated palagonite preclude the possibility of any marked loss of iron by leaching. It seems more than likely that the iron was volatilized as ferric chloride in a manner demonstrated in numerous industrial processes.[1] The increased fluidity of the uppermost lava at the moment of explosion would render it remarkably susceptible to the loss of any volatile constituent. In places the white tuffs are saturated in chlorides, which, however, may be of organic origin.

Intermittent activity.—Although some of the vents show a simple phase due apparently to one stage of extrusion following the initial explosion, others exhibit characteristics that prove irregular fluctuations which occasionally must have been accompanied by surface solidification. Evidence of minor fluctuations is shown by the surface lava frequently interbedded with the inclined pyroclastics. When solidification of the cap has occurred, renewed activity has been initiated by later explosions which probably were caused by the local fracturing of the chilled margin that insulated the lava from the gravels. This fracturing might be due to a subsequent burst of activity, possibly accompanied by a minor movement along the original fissure. Intermittent explosions could also be caused by the influx of water into the heated gravels.

The resaturation of the gravels would be expected from the close proximity of these vents to old mountainous masses which at the time of extrusion certainly rose as steptoes above the flat-lying lava flows. The precipitation on these steptoes following the old drainage channels would have seeped beneath the basalts.

Where the column was still molten these later bursts of steam appear to have risen like great bubbles which at times were caught in the more viscous near-surface lava. This action is considered to

[1] J. C. Hostetter, H. S. Roberts, J. B. Ferguson, "The Volatilization of Iron from Optical Glass Pots by Chlorine at High Temperatures," *Jour. Amer. Ceramic Soc.*, Vol. II (1919), pp. 356–72.

G. A. Bole, R. M. Howe, "The Rôle of Chlorides in the Volatilization of Ferric Iron," *Trans. Amer. Ceramic Soc.*, Vol. XVII (1915), p. 125.

explain the circular cavities frequently exposed in the upper part of the crater filling. These cavities, which range from two to at least twenty-five feet in diameter, are lined with bluish-gray opaque lava. This usually exhibits a granular appearance, but in places shows glassy surface features. The columns invariably radiating from these centers prove that they presented cooling surfaces.

In a similar manner the chilled sideromelan formed by a later inundation might rise as a hydrated mass held together by its steam saturation. This interpretation explains a remarkably circular body exposed in the upper part of one of the craters. It consists of a solid mass of yellow palagonite about fifty feet in diameter. The outer margin of this breccia is altered to a bluish gray, presumably by dehydration. The induration accompanying this alteration causes it to stand up like a circular wall about 5 feet thick. Surrounding this an exceptionally aphanitic basalt exhibits platy jointing parallel to the contact normal to which, at a distance of a few feet, radiate basaltic columns.

DESCRIPTION OF THE INDIVIDUAL VENTS

Many adjacent vents show pronounced alignment which testifies to their common ancestry. The zone to which the exposures are confined has an approximate orientation of N. 35° W. Although this direction shows the average trend, its sharp definition into an area of about 10 miles by 1 may be the result of chance, for it does not coincide closely with the major axis of several of the main lines or craters. Since the most important exposures are confined to the southern half of the zone the author will briefly describe the individuals in numerical order from the south without regard to their individual importance. This order permits the logical association of the related units.

About 3 miles south of Asotin on the Washington side, the canyon cuts the flaring margin of a crater (1) (Fig. 1) at some 700 feet above the river. From its single exposure, which is about 300 feet deep, the crater appears to have an axis of N. 30° W. Its explosive origin is proved by the exposure at its southern contact of the brecciated margin of the older flows overlain by a thin layer of palagonite on which the glassy border of the central filling rests.

At about a hundred yards from its eastern margin lies another

crater (2) which presents important evidence on the mechanism. In spite of its close proximity it appears to have no direct connection with the one previously described. It has an elliptical outline close to a third of a mile in length and, at its northern rounded end, about 100 yards in width. Its axis, which is approximately N. 45° W, exactly coincides with the southern end of another crater (3) from which it is separated by about 200 yards.

This crater (2) is at least 600 feet deep, although again the actual feeder is not exposed. Its main explosive beveling cut an earlier phase represented on its southern margin by a small hackly mass overlain by pyroclastics. This explosion must have been followed by extrusion, for the crater is lined with inclined pyroclastics. The two ends of the elongate crater filling, however, solidified at a time of withdrawal, forming a columnar jointed mass which about half filled the crater. The lava in the still fluid central part must have then risen very slowly, sending out thin frothy sheets over the already solidified ends, gradually building a horizontally bedded crater filling against the inclined marginal pyroclastics. The central column with irregular outline finally solidified with coarse radiating columns.

Numerous important details are furnished by this southern exposure. The pyroclastics capping the earlier hackly phase contained the quartz grain imbedded in sideromelan. At about 400 feet above the river a remarkably heterogeneous conglomerate is exposed at the base of the crater filling. This presumably was extruded at the first rise of the lava. In its lower part this thin bed is made up chiefly of small waterworn bowlders and local accumulations of quartz sand, the grains of which frequently are imbedded in the thin film of manganese oxide coating the pebbles. Above this, coarse rounded blocks of basalt are imbedded in palagonite. Some of the basalt is in bomblike masses with vesicular centers and chilled margins. The massive blocks, which range up to 2 feet or more in diameter, exhibit an undulatory surface that suggests a primary origin, but they show no perceptible chilling. Although larger and less regular than usual, they probably have the pillow-like origin postulated by the author. The bombs might have had a similar origin if only partially solidified and saturated with water vapor at the time of the explosion.

In the upper part of this same phase is a remnant of a very large gas cavity which originally must have been about 30 feet in diameter. Above this, in the lowest of the thin horizontal flows which form the crater filling, are local masses of unaltered granular sideromelan. The extreme resemblance of this friable glassy substance to the typical palagonite tuff furnishes evidence on the origin of the latter.

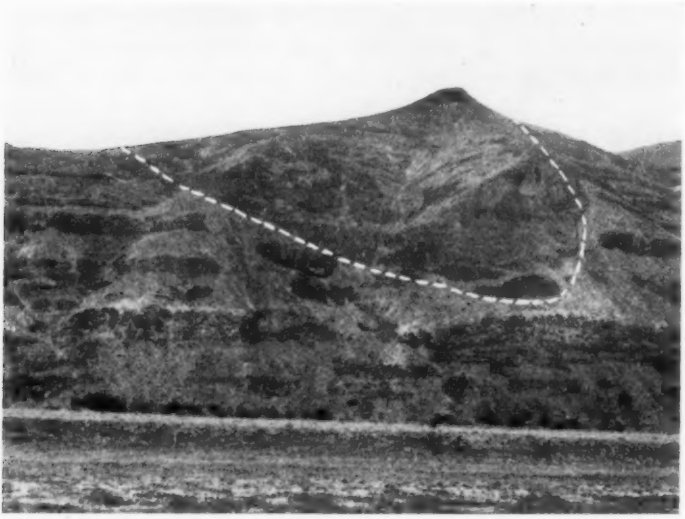

FIG. 2.—The south end of the elliptical crater (4), about a mile and a half south of Asotin, viewed from the western side of the river. On the right columns radiate from a large gas cavity.

The southern end of the associated vent (3) to the north has a similar outline which is well defined in the stream valley between them. The absence of exposures prevents an estimate of the length. The only interesting phase noticed in a rather poor exposure is the round mass of marginally dehydrated palagonite that has been previously described.

At about a mile farther to the north on the east side of the river is the southern end of another series of aligned vents. The most southerly of these (4) is excellently exposed (Fig. 2). It consists of

a relatively homogeneous mass filling a flaring crater about a quarter of a mile in length. A gully fortunately cuts it to sufficient depth to expose a fissure-like feeder which is about 200 feet wide. An inclined tuff bed suggests the position of the northern margin of this unit; but on the same axis, about 150 yards farther to the north, another fissure-like body (5) is exposed. A few remnants of the

FIG. 3.—At the bend of the river east of Asotin, showing the elliptical plug (6), and above it the two remnants of the crater filling resting on inclined pyroclastics.

flaring walls prove that this also fed an explosive crater. The exposed length is nearly a quarter of a mile. Its northern end is covered by a landslip, but a deep gully about another quarter of a mile to the north fails to reveal it.

In spite of this fact another crater (6) is exposed on the same axis at about three-quarters of a mile beyond the intermediate vent (Fig. 3). The elliptical plug that fed this crater is very clearly defined, but the flaring walls have survived erosion only on the eastern side. This massive remnant of the crater filling, rising about 700 feet, lies at the bend in the river almost due east of Asotin. The fine

breccias underlying it, with minor irregularities in the strike, dip toward the crater at about 35 degrees. Toward the top the angle is less extreme. Here the palagonite pyroclastics are of especial interest both from their content of calcined siliceous pebbles and from their definite proof of upward movement (Fig. 4).

Immediately to the north of this crater and almost intersecting it lies one of the most complex of the vents. It consists of two units (7 and 8), one of which is exposed about a quarter of a mile up the

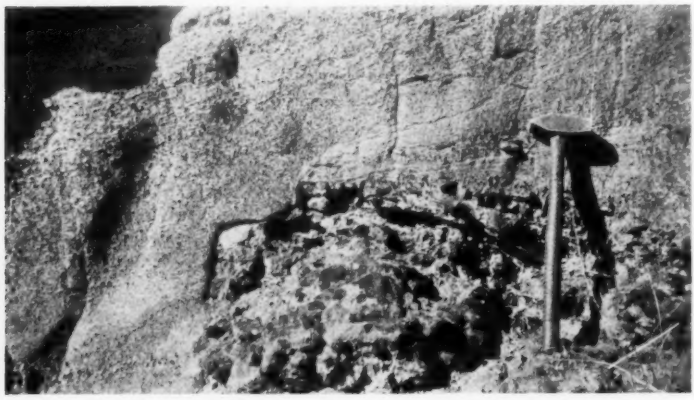

FIG. 4.—The lines of flowage in palagonite pyroclastics, showing evidence of upward movement (6).

deep gully which enters the Snake at the bend; the other outcrops on the north side of the main canyon. As it swings toward the west, the river, converging with the crater, has removed most of its southern wall. Although the relationship of the two units is masked, their alignment of N. 70° W. implies a common genesis.

The eastern one (7), however, solidified prior to the final activity. A limited exposure indicates that this unit was welling into a flow at the moment of solidification. At about 200 feet above it palagonite beds dip toward the northwest, testifying to a later continuation of activity that was probably associated with the other unit (8).

This larger unit (8), which lies directly opposite Asotin, is about three-quarters of a mile long (Fig. 5). It shows a large variety of phases which are partly due to the diagonal on which it is cut. The

western end, which is bisected by the river, has suffered erosion to a greater depth than the eastern end, where the vent is higher on the canyon wall. In consequence, toward the eastern end the older flows, which form the original crater wall, still survive.

A hackly crater filling rises from pyroclastics resting on the beveled edges of these earlier flows. This crater filling now forms only a thin veneer facing the river, for it has been cut by a later fissure-like intrusion that curls into an extrusion above it. This later

FIG. 5.—Looking east along the later dikelike body (8) opposite Asotin. The curve of the columnar jointing suggests the proximity of the southern wall. The elliptical plug (6) is exposed to the south of the main gully.

intrusion, about 150 yards in width, is bisected by the river farther to the west. In spite of its size when it finally solidified it was still capped to a great extent by palagonite breccias.

Underlying the hackly mass at the river's edge the original flaring crater exhibits elliptical basaltic bowlders in a fine palagonite matrix. These bowlders presumably are of pillow origin. On top of this earlier cap is a coarse basaltic breccia. Unlike the ellipsoidal variety, some of the blocks in this breccia still show their columnar outline, although possibly owing to friction they are slightly rounded. The matrix between these blocks is a mixture of palagonite and the white tuff with an occasional accumulation of a soil-like material containing quartz grains. This basaltic breccia was proba-

bly formed by the disruption of a thin cap of basalt. The superficial solidification of this earlier crater filling is inferred by the absence of explosive beveling.

On top of this breccia and underlying the extruded lava that presumably caused it is a bed of palagonite some 10 feet thick. Imbedded in this are two silicified logs and several smaller wood fragments. The broken ends of the logs are exposed in deep cavities in the cliff, dipping at low angles toward the adjacent margin of the later vent. The cavities probably are formed by the breaking of the petrified logs which erosion at one time must have left protruding from the soft matrix.

The smaller fragments are of opal, but the larger ones, with a diameter of about 1 foot and 3 feet respectively, are both of crystalline quartz, although still retaining their cell structure. The larger one is hollow with a siliceous border about ten inches to a foot in thickness. The outer margin, to a depth of about half an inch, is of a white opal partially altered to a fibrous type.

Their position above the breccia and below the extruded lava implies that they must have been carried, together with the palagonite, from beneath the basaltic flows and deposited at the mouth of the vent. This movement would explain their common orientation. If the fossilization is considered to have taken place in their present matrix without transportation, the crystallinity of the two large logs would be difficult to explain, but it would not be abnormal in view of their contact with the lava. The brownish quartz-bearing material, which occasionally forms the matrix of the bowlders, probably represents the soil in which the wood was originally fossilized at the time of the initial flows. This material also contained fragments of fossilized wood.

Along the western half of this fissure (8), which is approximately 150 yards wide, the river has removed the southern wall, but the sharp curve of the columnar jointing indicates that the outer margin was not far distant. The northern wall is slightly flaring. Judging from the near-surface characteristics of its lava, this end of the vent probably solidified at about 200 feet above the river. Any capping breccias would, however, have been removed by erosion.

Farther to the east, where the exposures are higher on the valley wall, the vent is capped largely by the palagonite breccias

into which it intrudes. These intrusions are partly in the form of irregular glassy apophyses and partly in well-defined dikelike bodies. Even the latter frequently come to an abrupt end in the yielding breccias which show local exposures up to a hundred feet in thickness.

A gully in the vent close to the river gives evidence on the formation of the dikelike masses. After the solidification of the surface of the fissure filling to a fine jointed hackly mass the still fluid lava

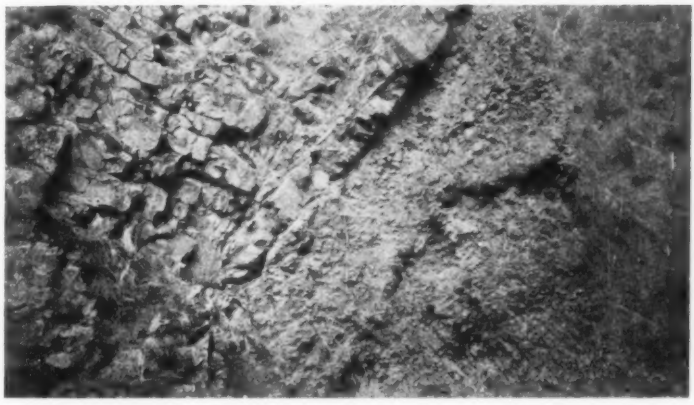

FIG. 6.—The brecciation of the solidified surface of the fissure filling (8) by a local advance of its own partially chilled lava.

below forced its way up again in a thin clean-cut intrusion about 10 feet thick. This intrusion brecciated the hackly mass and then solidified with fairly well-defined horizontal columns (Fig. 6). The viscosity of this partially chilled intrusion prevented the injection of minor apophyses into the unconsolidated breccia.

Toward the east, in a subsequent burst of activity, the still molten column succeeded in cutting through the pyroclastics, brecciating the earlier dikelike masses with which it came in contact. This renewed activity resulted in flows several hundred feet above the solidified portions of the vent to the west. Its highest exposure, some 500 feet above the river, shows it welling into successive flows. Although each extrusion apparently was accompanied by marginal solidification the vent locally continued its activity without any ap-

preciable withdrawal of the lava. Judging from the previously mentioned inclined tuff bed above the eastern unit (7), this activity probably was continued for a hundred yards or more to the east.

The steep bank at the edge of the river shows the western end of this elongate vent cross-cutting two horizontal flows. This sharp contact is almost vertical and lacks the usual palagonite bed. The two flows which it apparently intrudes are also cut within 150 yards by a hackly mass (9) which appears to form the southern end of another crater filling with an axis of approximately N. 15° W. Its feeder is not exposed, and much of the mass rests on coarse basaltic bowlders which may have been derived from brecciation of initial pillow lava. This mass apparently has been cut by the tapering eastern end of the elongate vent (8), but the exposures are far from satisfactory. The upper surface back from the river grades into a hackly flow that completely masks the relationship. One exposure of basalt, however, has resisted erosion and stands up as a narrow ridge about 40 feet wide and 150 feet long. This is directly in line with the exposure by the river and presumably was formed by a curtailed continuation of activity.

On this axis another mile to the northwest is a large dome-like mass (11) of hackly basalt on the eastern side of Tammany Creek. This mass, which is at least a quarter of a mile in diameter, exhibits inclined pyroclastics on three sides dipping under it. This relationship strongly suggests that it is formed by another crater filling. Immediately adjacent to this another mass (10) of basalt rises from a soil covering. It appears to be formed by a fissure filling about 90 yards in width. It has clean-cut straight margins extending to the southern side of Tammany Creek a distance of about 600 yards. Its axis is N. 40° W.

Directly on this line, at about three-quarters of a mile to the northwest, a resistant exposure extends into the river from its western bank. This presumably is due to a continuation of the elongate vent (10). Above the exposure and just to the north irregular flows appear to form the southern wall of another massive crater (12) filling which rises in a sheer cliff nearly 400 feet above the river. This basaltic mass with its fan jointing measures about 250 yards between the beveled edges of the flows that appear to form its

crater walls. From physiographic evidence I. C. Russell[1] considered the position of this block to be due to landslip. In that case it may well represent a displaced crater filling which originally had capped a continuation of the adjacent elongate plug.

Immediately to the south lies a massive exposure of fine palagonite breccias which have been quarried as the Asotin sandstone. This deposit was also observed by Russell[2] and considered by him to have been formed by the contact of a flow with a local body of surface water. The relationship of this mass to the crater was not definitely established. If it is in place it probably forms a local cap of the vent. If, however, it has slipped with the crater filling it probably represents an extruded mass deposited on the lip of the crater by the rise of lava. The inclined pyroclastics that define the southern margin of the original crater are exposed for about 250 yards farther to the northwest in line with the fissure-like vent at the river. The gully in which they are exposed is of local interest as the site of a prospective oil well which at a depth of over a thousand feet is still in basalt.

The last crater (13) observed is about $3\frac{1}{2}$ miles farther to the northwest on the southern bank of the Snake River (Fig. 7). The eastern end, which is cut diagonally by the canyon wall, shows the vent to be elongated on an approximate east-west axis. This line roughly parallels the zone of later deformation formed at the junction of the Lewiston Basin and the Union Plateau on the opposite side of the river. The contact follows the beveled margins of the flows from the valley bottom to a height of about 300 feet.

Well-developed columnar jointing of the crater filling rises normal to an inclined bed of tuffs and sediments some 20 feet or more in thickness. This bed at the base of the crater contains a large amount of quartz sand, which in places appears to have been reworked by local agencies. On this sand lies the white tuff, intermixed in its upper part with the typical palagonite which overlies it. All three members extend up the hill, although the sand thins out rapidly. Unfortunately exposures were not sufficiently satisfactory to permit an accurate interpretation of the history farther to the west.

[1] I. C. Russell, *op. cit.*, p. 77. [2] *Ibid.*, p. 35.

General considerations.—Although explosive beveling undoubtedly was the major factor in the formation of the craters, it seems probable that they were deepened to some extent by the fluctuations of the lava column. The still molten lava capping the crater might have withdrawn after a period of extrusion, leaving the beveled edge of the solidified flow. Unfortunately the actual point of extrusion has often been removed. In consequence conclusive evidence on this mechanism was not obtained.

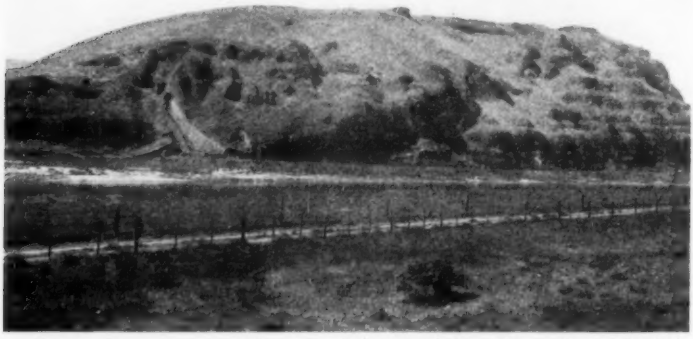

FIG. 7.—The most northerly crater (13), viewed from the northern side of the Snake River.

It is difficult to estimate the amount that these vents contributed to the total thickness of the basalt in the vicinity. The unusual concentration of basaltic fragmental material between the adjacent flows, as well as their high volatile content which is indicated both by their numerous gas cavities and their frequent deuteric alteration, suggests the proximity of events similar to those described. The Asotin Craters, however, are relatively late and cut most of the flows that have survived erosion. The chilling at depth probably resulted in premature solidification, but the fluidity of the lava was not affected enough to cause any appreciable doming of the extruded material.

The author acknowledges the valuable assistance of Mr. Aaron Waters in the field and the helpful advice of both Professor G. E. Goodspeed and Mr. Waters.

THE DIRECTION OF THE STRESSES PRODUCING GIVEN GEOLOGIC STRAINS[1]

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ABSTRACT

Theoretical and experimental data are herein presented which afford a means of determining to within a quadrant of arc, or less, the direction of the stress which has caused a given deformation, and whether the strain has been rotational or non-rotational.

INTRODUCTION

There was a time when geologists generally were of the opinion that the stress producing folding or schistosity necessarily acted at right angles to the direction of the axes of the folds, or to the trend of the schistosity. More recently, however, Leith[2] and Mead[3] have called attention to the fact that folds may be produced at variable angles to the causal stress. From this they each conclude that at our present state of knowledge we do not know whether the stress causing such structures as the Southern Appalachians was applied obliquely or at right angles to the trend of the range.

During the past year the present writer has been considering from a theoretical and experimental point of view the problem of how to distinguish between the deformation produced by oblique stress and that produced by perpendicular stress. The results of that investigation are herein presented.

THEORETICAL ANALYSIS

Following the usage introduced by Leith,[4] geologic strains may be thought of in terms of the "strain ellipsoid" which has been

[1] The writer is indebted to R. T. Chamberlin for criticisms of the first draft which have led to important improvements.

[2] C. K. Leith, *Structural Geology* (revised, 1923), pp. 21–28.

[3] Warren J. Mead, "Notes on the Mechanics of Geologic Structures," *Journal of Geology*, Vol. XXVIII (1920), pp. 522–23.

[4] *Op. cit.*, p. 22.

formed by the deformation of an imaginary sphere within the rock mass.

A strain in which the long axis of the strain ellipsoid is always perpendicular to the greatest compressive stress may be termed a non-rotational strain.

A strain in which the axes of the strain ellipsoid have been rotated with respect to the greatest compressive stress may be termed a rotational strain.

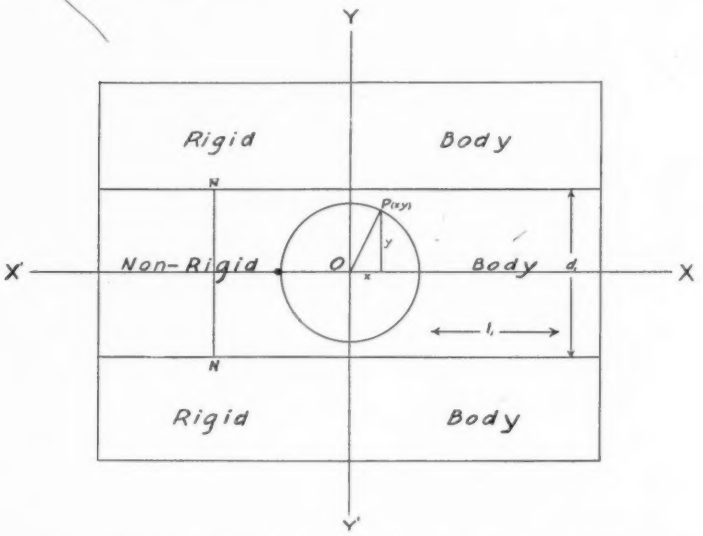

FIG. 1.—Diagram of hypothetical plastic body between two parallel rigid bodies showing the inscribed circle and the co-ordinate axes before deformation.

There commonly occur in geologic structure situations where weaker deformable bodies of more or less linear extent are bounded on one side or both by stronger relatively rigid bodies. When deformation occurs these rigid bodies serve to transmit the stress against the weaker bodies which undergo marked deformation. Examples of this sort are seen in the folding of the weaker sediments filling geosynclinal troughs, in the schistosity developed in a thin

shale stratum due to shear of the more rigid strata above and below; and the same principles are involved in the folding of weaker overlying sediments due to horizontal movements along an old buried fault.

Let us analyze an ideal case of deformation of this type. The fullest analysis of this problem must be in three dimensions, but since the geologic exposures in most cases are confined to two dimensions, we shall limit the following analysis to surficial effects which are susceptible to field observation or map study.

Consider a deformable body of greater length than width which is bounded on both sides by parallel rigid bodies (Fig. 1). Let rectangular co-ordinate axes be so chosen in the plane which the surface most closely approaches that the X-axis is parallel to the long dimension of the body. Let the Y-axis intersect the X-axis at a point about the middle of the surface of the deformable body. Let a circle of radius R with its center at the origin be drawn upon the surface of the deformable body. Let a line NN be drawn across the body parallel to the Y-axis. Let P (xy) be a point on the circle.

The equation of the circle then is,

$$x^2+y^2=R^2 \tag{1}$$

Next let a uniform stress inclined at an angle ω to the X-axis be applied from each side. Then,

$F \sin \omega$ equals the compressive component
(Parallel to the Y-axis)

$F \cos \omega$ equals the tangential or shear component
(Parallel to the X-axis)

where F is the magnitude of the applied stress.

This stress will produce in the non-rigid body a combined compression parallel to the Y-axis; lengthening parallel to the X-axis; and shear parallel to the X-axis.

Let us assume that the lengthening, the shortening, and the shear are each uniform throughout the part of the body considered. Then during deformation the line NN will rotate through an angle θ in the direction of the couple produced by the tangential components of stress to a new position $N'N'$.

$$\text{Let } \frac{d_2}{d_1}=K_1 \quad \text{Definition of } K_1$$

where d_1 is the distance before deformation between two points in a line parallel to the Y-axis, and d_2 is the corresponding distance after deformation.

$$\text{Let } \frac{l_2}{l_1}=K_2 \quad \text{Definition of } K_2$$

where l_1 is the distance before deformation between two points in a line parallel to the X-axis, and l_2 is the corresponding distance after deformation.

After deformation the point P (xy) on the initial circle will have moved to a new position P' $(x'y')$ such that,

$$y'=K_1 y \text{ or } y=\frac{y'}{K_1}$$

and

$$x'=K_2\, x+y' \tan\theta \text{ or } x=\frac{x'}{K_2}-\frac{y' \tan\theta}{K_2}$$

Substituting these values of x and y in (1) we get,

$$\frac{x'^2}{K_2^2}-\frac{2\,x'y' \tan\theta}{K_2^2}+\frac{y'^2 \tan^2\theta}{K_2^2}+\frac{y'^2}{K_1^2}=R^2 \tag{2}$$

which is the equation of the distorted figure of the initial circle.

From analytical geometry the general equation of the second degree may be written,

$$Ax^2+Bxy+Cy^2+Dx+Ey+F=0 \tag{3}$$

and if B^2-4AC is negative the equation represents an ellipse.

From (2) and (3),

$$B^2-4AC=\frac{4 \tan^2\theta}{K_2^4}-\frac{4 \tan^2\theta}{K_2^4}-\frac{4}{K_2^2 K_1^2}=-\frac{4}{K_2^2 K_1^2}$$

which is negative. Hence the deformation changed the initial circle into a strain ellipse.

Let ϕ be the angle that the long axis of the ellipse makes with the X-axis. Then from analytical geometry,

$$\text{Tan } 2\phi = \frac{B}{A-C} \tag{4}$$

Substituting in (4) the values from (2) and (3) we find that,

$$\text{Tan } 2\phi = \frac{2 \tan \theta}{\tan^2 \theta + \frac{K_2^2}{K_1^2} - 1}, \tag{5}$$

which expresses the relations between the angle ϕ of the orientation of the long axis of the ellipse with respect to the X-axis, the angle

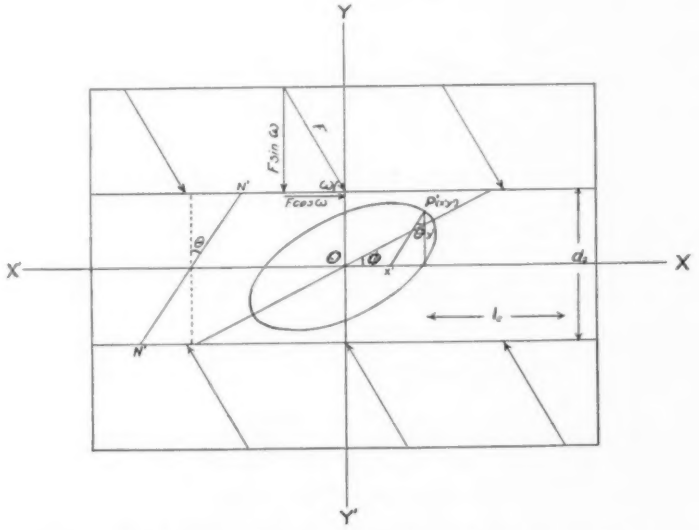

FIG. 2.—This shows the theoretical deformation of the plastic mass in Figure 1 due to a compressive stress applied at an angle ω to the X-axis. This also gives an idea of the relation between θ and ϕ.

of shear θ, the ratio of shortening parallel to the Y-axis K_1, and the ratio of elongation parallel to the X-axis K_2.

Before deformation

$$\theta = 0$$

$$K_1 = 1$$

$$K_2 = 1$$

ϕ is imaginary.

As deformation proceeds θ increases toward the limit 90 degrees, which can only be approached as the shear becomes infinite. K_1 decreases indefinitely from unity toward the limit zero. K_2 increases from unity by some indefinite amount.

Solving (5) for the limits of ϕ as θ goes from zero to 90 degrees, we find that with an infinitesimal amount of initial deformation θ is approximately zero, while K_1 and K_2 are approximately unity. Then,

$$\text{Tan } \theta = 0$$

and

$$\text{Tan } 2\phi = \frac{2}{\tan \theta} = \infty$$

Hence

$$2\phi = 90 \text{ degrees}$$

and

$$\phi = 45 \text{ degrees}$$

initially if the deformation is accompanied by shear of one side relative to the other.

As θ approaches 90 degrees, tan θ approaches infinity. Then

$$\text{Tan } 2\phi = \frac{2}{\tan \theta + \frac{K_2^2}{K_1^2 \tan \theta} - \frac{1}{\tan \theta}} \to 0 \text{ as } \theta \to 90 \text{ degrees}$$

If the angle ω which the applied stress makes with the X-axis should be 90 degrees, then the shear component $F \cos \omega$ equals zero, and only shortening an elongation of the body will result, unaccompanied by lateral shear of one side relative to the other θ remains zero and,

$$\text{Tan } 2\phi = 0$$

throughout the deformation.

Thus when stress is applied at an angle ω—different from 90 degrees—with the X-axis, the long axes of the strain ellipses form

at 45 degrees to the X-axis and, as deformation proceeds, rotate toward a position parallel to that axis. When the stress is applied at an angle ω—equal to 90 degrees—with the X-axis, the strain ellipses form with their long axes parallel to the X-axis and perpendicular to the greatest compressive stress. They remain so throughout the deformation.

In order not to misinterpret these results it must constantly be borne in mind that this stress is being transmitted by rigid bodies against a non-rigid body, and that the X-axis as it is here used is arbitrarily chosen parallel to the contact between the rigid and the non-rigid bodies.

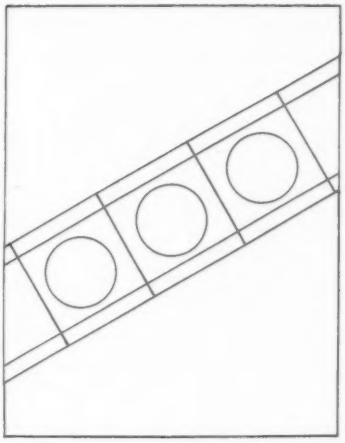

FIG. 3.—The experimental apparatus before deformation. The rigid bodies are wooden blocks; the plastic mass is modeling clay. The rectangles are longitudinal and transverse threads imbedded in the surface of the clay. The circles are stamped and then painted a contrasting color.

EXPERIMENTAL VERIFICATION

Apparatus: The apparatus used consisted of two blocks of wood formed by sawing a rectangular block diagonally across at an angle to the long dimension of the block. Modeling clay was packed between the diagonal ends of the blocks forming a strip of about the proportions shown in Figure 3. Two straight threads were imbedded in the surface of the clay parallel to the contact between the clay and the diagonal edge of the block. They were set far enough away from the edges of the blocks not to be affected by slip phenomena near the contact. Cross-threads were imbedded in the surface of the clay at right angles to these at intervals along the strip of clay. Circles were stamped upon the surface of the clay and painted a contrasting color. The blocks were free to move either toward each other or laterally. Uniform stress perpendicular to the square ends of the blocks was applied. Measurements were recorded of:

d_1, the distance between the longitudinal threads before deformation; d_2, the distance between the threads after deformation; θ, the angle through which the cross-threads were rotated; ϕ, the angle that the long axes of the ellipses made with the longitudinal threads. The lengthening was found to be negligible.

ω was not recorded, though in different sets of apparatus values of ω ranging from 30 to 60 degrees were used. For all these values the same qualitative results were obtained.

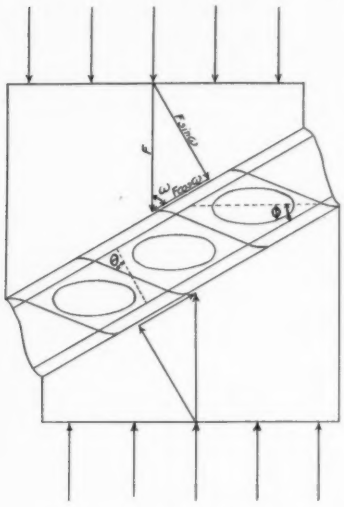

FIG. 4.—This shows how the forces were applied and the effect produced upon the modeling clay.

Observations: Many experiments were tried, all of which showed the same qualitative results as those recorded in Table I. Aside from the numerical relations it is rather significant that tension cracks were formed at right angles to the long axes of the ellipses in a number of the experiments. The observed and calculated values for ϕ given in the table afford a measurement of the agreement between theory and experiment.

In order to learn the relation between the axes of folds and the orientation of the strain ellipse, experiments were made in which more competent coverings were placed over the surface of the clay. In some experiments paper, in others tinfoil, and in still others rubber-membrane covers were placed firmly on the surface of the clay. In each case folds resulted with their axes parallel to the long axis of the strain ellipse.

GEOLOGICAL APPLICATION

As was mentioned previously, certain geologic structures frequently have many features similar to those of the ideal type on which the foregoing reasoning is based. It seems, therefore, that any

generalizations which may be derived from consideration of the ideal type may be applied, qualitatively at least, in interpreting similar geologic structures.

The angle ϕ may be determined in two ways: (1) If the surface considered is the areal "plane," ϕ will be the acute angle between the axes of the individual folds and the main trend of the belt or range. (2) For smaller units, such as a stratum of shale between two strata of quartzite, it is frequently possible to determine the flow

TABLE I

EXPERIMENTAL DATA

Exper. No.	d_1 Cm.	d_2 Cm.	K_1	θ Degrees	ϕ Observed	ϕ Calculated
Ia	2.80	2.56	.9143	20.0	30.0	33.1
Ib	2.80	2.46	.8786	38.7	30.15	29.8
Ic	2.80	2.34	.8357	54.3	20.5	24.2
IIa	2.37	2.20	.9283	19.0	29.0	33.7
IIIa	3.0	2.85	.9505	15.0	33.0	35.6
IIIb	3.0	2.73	.9100	25.5	33.0	32.7
IIIc	3.0	2.63	.8767	44.2	30.0	28.7

cleavage, which, according to Van Hise[1] and to Leith,[2] is parallel to the long axis of the ellipse. Then ϕ would be the angle between the flow cleavage and the bedding plane.

For qualitative purposes it is not necessary to know K_1 and K_2 because only the quantitative results are affected by these constants.

CONCLUSION

On the basis of the foregoing considerations the following conclusions seem to be valid.

1. That uniform stress applied obliquely to a deformable body of a more or less linear extent and bounded on one side or both by rigid bodies produces a combined shear and elongation parallel to the line of contact between the bodies, and a shortening at right angles to this. This deformation in turn produces ellipses of circles, flow cleavage, or folds oriented in *en échelon* fashion along the body

[1] Charles R. Van Hise, "Principles of Pre-Cambrian Geology," *Sixteenth Annual Report of the U.S. Geol. Survey*, Part I (1894–95), p. 638.

[2] *Op. cit.*, p. 124.

at an inclination of 45 degrees, or less, to the main trend of the deformed area. This orientation of structures approaches parallelism to the main trend very slowly as deformation proceeds, except when the stress is applied approximately at right angles to the trend.

Conversely, the presence of *en échelon* folds arranged in such a manner indicates that the stress was applied obliquely and that rotational strain was the result.

2. That when uniform stress is applied at essentially right angles to a non-rigid body under the conditions just stated, narrowing and elongation will occur, but there will be no lateral shear of one side relative to the other. The long axes of the strain ellipses, flow cleavage, or axes of folds will be parallel to the main trend of the belt and at right angles to the greatest compressive stress.

Conversely, when the long axes of the strain ellipses, flow cleavage, or axes of folds are aligned parallel to the main trend under these conditions, either the applied stress was oblique and the deformation was practically infinite, or the applied stress was at essentially right angles and the deformation was non-rotational strain. Since, however, for any but very small bodies deformation sufficient to rotate the *en échelon* structures, which have been produced by oblique stress, into parallelism with the main trend seldom, if ever, occurs geologically, only the latter alternative remains.

Assuming that the foregoing results are valid, we find by their application to the Southern Appalachians, in which the axes of the individual folds are parallel to the main trend of the range, that the greatest compressive stress must have been applied at essentially right angles to that part of the range. The resulting strain, considered in the horizontal plane, was non-rotational.

THE STRAIN ELLIPSOID AND APPALACHIAN STRUCTURES

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ABSTRACT

In the folding and faulting of mountain ranges by straight compression (non-rotational stress) the direction of easiest yielding, and hence the longest axis of the applied strain ellipsoid, is upward. The intermediate axis of the ellipsoid of strain is parallel to the trend of the range. The strike of whatever thrust faults develop should be in line with the intermediate axis and they should dip at approximately 45° in either direction. If produced by forces acting as a couple in horizontal plan (rotational stress), the direction of elongation (longest axis of the ellipsoid) should be horizontal and resulting shearing fractures should be vertical planes cutting across the trends of the folds at approximately 45°. The Appalachian thrust faults strike with the trend of the folds, thus agreeing with the first case and indicating that the immediate strain was dominantly non-rotational in horizontal plan.

INTRODUCTION

From the early days of Appalachian mountain studies it has generally been taken for granted that the Appalachian folding was produced by compression at right angles to the trend of the range. During the last couple of decades, however, Leith has recognized the possibility that folding of this sort may have been developed just as well, so far as we know, by rotational as by non-rotational stresses, and in his clear-cut way has strongly impressed his students with the necessity for keeping the two alternative possibilities sharply in mind. Much more recently Mead, using a frame apparatus, has produced miniature folds of the Appalachian type both by compression which was applied perpendicular to the resulting folds and by forces applied obliquely to them.[1] While a judicial, open-minded attitude is maintained in this paper, Mead is inclined to favor the view that the Southern Appalachians were folded and faulted by rotational stresses. On the other hand, as brought out in the preceding article,[2]

[1] Warren J. Mead, "Notes on the Mechanics of Geologic Structures," *Journal of Geology*, Vol. XXVIII (1920), pp. 505-23.

[2] M. King Hubbert, "The Direction of the Stresses Producing Given Geologic Strains," this number, pp. 75–84.

a mathematical and experimental analysis of the operation of the stresses producing rotational and non-rotational strains has led M. K. Hubbert to the conclusion that the compressive forces which have caused the folding of mountain ranges like the Southern Appalachians have operated essentially at right angles to the axes of the ranges.

FOLDING AND FAULTING BY NON-ROTATIONAL STRESS

It seems to the present writer that for comparison the method of the strain ellipsoid may profitably be applied to the experimental folds and the Appalachian folds in turn, and the correspondences and differences noted. When a sphere is deformed into an ellipsoid, the planes of no distortion or planes of maximum shear are inclined at approximately 45° to the greatest and least axes of the ellipsoid.[1] These shearing planes intersect parallel to the intermediate axis of the ellipsoid. Hence the orientation of the strain ellipsoid affords a useful method of analysis. In a non-rotational strain (pure shortening by direct compression) folds form with their axes at right angles to the direction of compression,[2] and the related thrust faults also strike at right angles to the compression or shortening[3] and dip at angles of approximately 45°. In this case the longest dimension of the strain ellipsoid (direction of easiest relief) is upward (in the field sense), and the intermediate axis of the ellipsoid is horizontal and parallel to the strike of the fault planes. This is just as in the Appalachians, where the strike of the thrust faults is NE.-SW., parallel to the trend of the folds, and the thrust fault planes dip for the most part SE. at angles somewhat less than 45°.

DEFORMATION BY ROTATIONAL STRESS

Figures 1 and 3 represent the experimental results obtained by Mead from the application of rotational stress. So far as one can see, the force was applied in the same manner in both instances. But the materials which were deformed were of different competency and the final results quite different. In the first case, paraffin made brittle

[1] C. K. Leith, *Structural Geology* (revised ed., 1923), pp. 22-23.

[2] W. J. Mead, *Journal of Geology*, Vol. XXVIII (1920), Fig. 11, p. 518.

[3] *Ibid.*, Fig. 2, p. 509, and Fig. 3, p. 510.

by chilling formed a network of fractures; in the second case, plastic wax covered with a sheet of tinfoil developed folds. If these results are to be applied to mountain structures, it is clear that certainly in the case of the folds, and presumably also in the case of the fractures, the surface of the coated sheet of rubber of the experiments is to be analogous to the earth surface. This surface will be called horizontal for sake of brevity.

Faulting.—In non-rotational strain the longest axis of the ellipsoid for our problem is vertical. In Figure 1, produced in a rotational strain, the greatest elongation, and hence the longest axis of the ellipsoid, is horizontal. If this, like Figure 3, is to be applied to mountain structures, the longest axis would be parallel to the surface trend of the range. In Figure 1 the fractures due to shearing are parallel to the sides of the rubber sheet, and so cut across the elongation at 45°. The intermediate axis of the ellipsoid is vertical. Tension cracks opened parallel to the least axis. Mead states that in Figure 1 there were also two thrust faults striking normal to the tension cracks and dipping 45° in either direction. Though very inconspicuous in this experiment, he states that the prominence of this set relative to the other shearing fractures varies with the thickness and brittleness of the paraffin coats (pp. 512 and 513).

Folding.—In Figure 3 the tension cracks, and hence the least axis of the ellipsoid, were the same as in Figure 1. But here the folds have resulted more from upward than from lateral relief. So far as the folded material itself is concerned, the longest axis of the strain ellipsoid would therefore seem to be vertical, and the intermediate axis horizontal, parallel to the trend of the folds.

How can this different orientation of the strain ellipsoid result from similarly applied force? It appears to be a question of the direction of easiest relief being different in the two cases. The difference arises from the different behavior of the brittle paraffin and the plastic wax covered with tinfoil. The very thin coating of brittle paraffin deformed very closely with the underlying rubber and the elongation was horizontal. The plastic wax, covered with tinfoil which supplied a small amount of competency, did not follow the deformation of the rubber sheet so closely, and found easier accommodation upward. In this deformation an effective compressive

stress operated in the direction of greatest shortening, and the folding was the result of it.

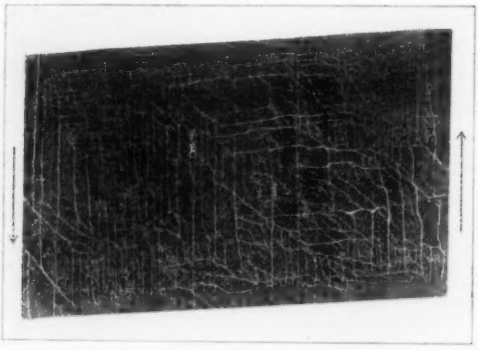

FIG. 1.—Fractures produced in paraffin coat on rubber sheet by shearing. The arrows indicate the direction of movement, and the shape of the figure shows the amount of distortion. From W. J. Mead.

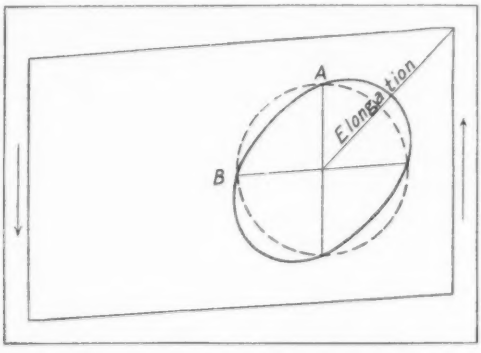

FIG. 2.—The strain ellipse placed on Figure 1. A and B are the lines of shear at 45° approximately to the direction of elongation or the longest axis of the strain ellipsoid.

COMPARISON WITH APPALACHIAN STRUCTURES

If we turn to the Appalachian folds, upward yielding seems to have dominated yielding laterally in the long dimension of the range. Corroborating this is the testimony of the numerous faults. We

know that thrust faults strike parallel to the intermediate axis of the ellipsoid, while their dips are inclined approximately 45° to the two other axes. One of the chief characteristics of Appalachian structure is the close parallelism between the strikes of the many thrust faults and the axial lines of the folds. Both run NE. and SW., and some of

FIG. 3.—Vertical view of reproduction in plaster of paris of folds produced by shearing deformation. From W. J. Mead. Oriented as for the Appalachian folds.

the faults are more than 100 miles in length. Prevailingly the fault planes dip SE. at angles between 35° and 40°. They indicate that the intermediate axis of strain was horizontal, extending NE. and SW. with the range, while the shortest axis was NW. and SE. and the longest axis was vertical. This would point toward a strain which was essentially non-rotational in the horizontal plane, or to one in which any horizontal rotational factor played only a minor part in the immediate deformation.

If the thrust faults of the Appalachians developed under stresses

which were rotational in the horizontal plane, as in Figure 1, the majority of them should be vertical faults striking obliquely across the folds in the neighborhood of 45° to the axial lines, though a few, as in Figure 1, might be expected parallel to the folds and dipping 45° in either direction. These requirements do not fit very well the Appalachian case.

The conclusions from this method of analysis would seem to harmonize with those already expressed by Hubbert. In the immediate development of the Appalachian folds and thrust faults, compression perpendicular to the range seems to have been more important than rotational stresses oblique to the structures, though local adjustments may produce some oblique slippage on fault planes, particularly in the strips between the salients and recesses of the long, winding mountain chain. The ultimate source of the thrusting which produced the Appalachian structures is not here considered. Abundant evidence of rotational strain in *vertical* planes transverse to the range is afforded by the conspicuous low-angle overthrusts.[1]

[1] R. T. Chamberlin and W. Z. Miller, "Low-Angle Faulting," *Journal of Geology*, Vol. XXVI (1918), pp. 1–44.

REVIEWS

Eruptive Rocks, Their Genesis, Composition, Classification, and Their Relation to Ore-deposits. By S. J. SHAND. London, 1927. Pp. 360; figs. 43.

The subtitle of this little book indicates the broad field covered. Most of the discussions are very brief, for the principal portion of the book is devoted to Shand's classification of igneous rocks, which is here considerably modified from the preliminary papers published in the *Geological Magazine* of 1915, 1916, and 1917.

The scope of the first chapter, entitled "Eruptive or Igneous Rocks," is indicated by the subheads in the Table of Contents: "The Aims of the Study," "The Fundamental Problem," "The Proof of Fluidity," "The Presence of Water," "Fluid Inclusions in Crystals," "Pegmatites and Quartz Veins," "The Solubility of Water in Molten Silicates," "The Temperature of Crystallization," and "Eruptive Rocks and Mineral Veins." All this is contained in thirteen pages. Shand prefers the German usage of "eruptive" for this class of rocks. He objects to the term "igneous" because the rocks were not "formed by the agency of fire."

All bibliographical references are placed at the ends of chapters; but since the titles of papers are not given, it makes verification of statements difficult where several publications are credited to the same author.

Chapter ii, of seventeen pages, is on "The Fixed Constituents of Eruptive Rocks," and deals with the various important mineral groups: feldspars, pyriboles, micas, etc.

Chapter iii, eighteen pages, is on "The Fugitive Constituents of the Magma." Niggli's paper on "Die leichtflüchtigen Bestandteile im Magma" is not mentioned in the bibliography, although it is one of the most important contributions to the subject.

Chapter iv, "The Magma and Its Walls," twenty-four pages, treats of "The Pressure upon the Magma," "The Temperature of Freezing," "Minerals Used as Geologic Thermometers," "The Temperature of Flowing Lava," "Enclosures in Lava," "Assimilation of Silicates and Quartz," "Reactions of Silication and Desilication," and "Generalizations Regarding Assimilation."

In chapter v, "The Freezing of the Magma," Shand uses the terms "saturated" and "unsaturated," introduced by him in 1913, for minerals

which are stable or unstable in the presence of free quartz. This grouping forms an essential part of the system of classification which he develops in the succeeding chapters. He makes the statement that "leucite, nephelite, olivine, and a few other minerals are almost never found in rocks which contain free quartz or tridymite" (p. 93). Leucite, nephelite, and the sodalite minerals have never been found with free primary quartz.

Chapters vi to xiv treat of Shand's classification of igneous rocks; five of the chapters deal with generalities, and four give examples of rocks falling under the various groups. In this discussion, one is given the impression that no quantitative mineralogical system has ever been proposed before, while, as a matter of fact, there have been three or four. Several new terms are introduced to replace old and well-established words—thus "inset" (p. 110) for phenocryst, which is rejected on account of its combined Greek and Latin parentage. Under this objection the words "mineralogy," "leuco-granite," "subdiorite," "subtrachyte," and many, many more should be discarded.

Shand first subdivides his igneous rocks into two classes: the "eucrystalline" (well-crystallized) group, which includes the plutonites and the more coarsely crystallized dikes; and the "dyscrystalline" (ill-crystallized), which includes the microcrystalline, cryptocrystalline, and glassy rocks, whether they form dikes or lava flows.

The second subdivision is into five groups based on the relation of the silica to the bases. Actually the five groups are not quite comparable, since there are three main groups, with the third divided into three subdivisions as follows:

I. Oversaturated rocks (i.e., those containing free primary silica).

II. Saturated rocks (those containing neither free silica nor any unsaturated mineral [according to the statement on page 126] but including rocks in which the amount of free quartz or free tridymite lies between 0 and 10 per cent [on page 173].)

III. Undersaturated rocks (i.e., those which contain unsaturated minerals).

a) With magnesia, lime, and alumina unsaturated.

b) With alkalies unsaturated.

c) With alkalies and magnesia, lime, or alumina unsaturated.

Four groups, based on the relation of alumina to the bases follow:

a) A peraluminous group, characterized by primary muscovite, biotite, corundum, tourmaline, topaz, almandine, or spessartite.

b) A peralkaline group, characterized by soda-pyroxenes or soda-amphiboles, eudialyte, aenigmatite, etc., and by the virtual absence of the anorthite molecule in the feldspar.

c) A group characterized by common pyroxenes, amphiboles, olivine, fayalite, or epidote, with or without the addition of biotite.

This group is subdivided into—

c_1) A metaluminous group, characterized by any of the following associations: hornblende-biotite, hornblende-augite, biotite-augite, hornblende-biotite-augite; or by hornblende alone, or by primary epidote with or without hornblende or biotite. Olivine may also be present.

c_2) A subaluminous group, characterized by pyroxenes or olivine, without appreciable quantities of hornblende, biotite, or primary epidote.

In the determination of the type, a chemical analysis is in many cases necessary, and use is made of the calculation of the norm as in the C.I.P.W. system (which Shand calls the American system).

Now follow (p. 132) four groups based on the proportion of light to heavy minerals. Originally, in 1916, Shand proposed to divide the rocks into twelve groups according to the percentages of light and dark constituents. Here they are reduced to the following four:

1. Rock holding less than 30 per cent, by volume, of dark minerals are classed as leucocratic rocks.

2. Rocks holding more than 30 per cent, but less than 60 per cent, by volume, of dark minerals are classed as mesotype rocks. (Shand objects to the term "mesocratic" as having "a nonsensical meaning which ought not be perpetuated.")

3. Rocks holding from 60 to 90 per cent of dark minerals are classed as melanocratic rocks.

4. Rocks holding more than 90 per cent of dark minerals.

To take care of rocks which contain practically no dark minerals, Shand follows the reviewer's system of prefixing "leuco-" to the rock term; thus "leuco-granite." Since such rocks are quite abundant, one wonders why this was not made a fifth, or rather the first of five groups.

To distinguish these various groups, Shand separates them by the weight percentage of heavy to light minerals, taking a specific gravity of 2.8 as the division point. Thus a rock containing 17 per cent, by *weight*, of minerals having a greater specific gravity than 2.8, is said to have a *color* ratio of 17 per cent or *color* index of 17.

Finally, four groups are made based on the composition of the feldspar (p. 135). Here the system is no longer purely mineralogical, in spite of the fact that Shand says "it is a mineralogical system throughout" (p. 125). He says:

> The custom of the present time is to separate rocks in which alkaline felspars predominate from those in which plagioclase is dominant, and to make a third

division for rocks in which orthoclase and plagioclase are about equal. But since "orthoclase" includes varieties that are rich in soda, and plagioclase means anything from pure soda-felspar to pure lime-felspar, the practice is not good chemistry; and since soda appears in both terms of the ratio, it is not even good arithmetic [p. 132].

He then gives examples of certain rocks in which the amounts of the orthoclase, albite, and anorthite molecules are *calculated*, and uses them to show that rocks named according to the original definitions are incorrectly named. He says further:

> These examples show that the statement of the ratio of plagioclase to orthoclase, which is conveyed by such names as latite, dacite, andesite, to which we may add monzonite, diorite and granodiorite, as these names are currently defined, is worthless as a guide to the relative proportions of potash, soda, and lime in the felspars.

But in a mineralogical classification one is not concerned with the proportions of the potash, soda, and lime molecules in the rock, but with the proportions of the minerals actually present.

The divisions based upon these chemical molecules of feldspar are:

$$\text{Or. mol.} > \text{An. mol.} \begin{cases} 1.\ \text{Or. mol.} > \text{Ab. mol.} \\ 2.\ \text{Or. mol.} < \text{Ab. mol.} \end{cases}$$

$$\text{Or. mol.} < \text{An. mol.} \begin{cases} 3.\ \text{Ab. mol.} > \text{An. mol.} \\ 4.\ \text{Ab. mol.} < \text{An. mol.} \end{cases}$$

It may be remembered that the reviewer, in his own classification, originally divided the feldspars according to the Or, Ab, and An molecules, but, for the reasons stated above, soon changed to the actual minerals present. In a combined system, such as that given by Shand, one should have not only a chemical analysis of the whole rock but chemical analyses of the individual components as well. "It would be absurd," he says (page 109), "from a general petrographic point of view, that we should not be able to name a rock until we had determined the precise amount of every element contained in it"; yet he makes it necessary to have analyses of the feldspars to determine their exact position.

The term "mode" is used by Shand for the calculated components of a rock, including the feldspars in terms of "Or," "Ab" and "An" molecules. Such percentages may be far from the true mode, if by this term we are to understand the actual mineralogical composition.

Chapter xv, with eleven pages, deals briefly with meteorites; and chapter xvi and last, forty-three pages, covers the eruptive ore deposits.

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Forests and Water in the Light of Scientific Investigation. By RAPHAEL ZON, Director, Lake States Forest Experiment Station. Washington: Superintendent of Public Documents. 20 cents. Pp. 106; text maps 2; tables 21.

The paper aims to bring together and present the established facts regarding the relations of forests to water supply, rainfall effectiveness, and river erosion. The paper consists of two parts, in the first of which the problem is treated from the physical standpoint and in the second from the hydrometric.

Part I presents the results obtained by the physical method, or "through the measurement of individual factors." Data are tabulated relative to: air temperatures in the forest and in the open, relative humidity in forested and treeless regions, soil temperatures within and outside the forest, soil temperature fluctuations within and outside the forest, precipitation in forested and treeless regions, interception of rainfall by tree crowns, interception of snow by forests, transpiration by trees, loss of water to streams in forested and cultivated areas. These data are critically discussed and general conclusions drawn concerning the effects of forests in obstructing run-off, conserving precipitation, and influencing erosion.

In Part II, under the heading "Results by the Hydrometric Method," much river-gauging data is given and analyzed. The rivers from which data are taken are those of North America, Europe, and India. Five pages are devoted to two- and three-sentence summaries of changing conditions in the flow of specific springs after deforestation of the region in which they are located. At the close is a short summary of observed facts concerning the effects of forests upon stream flow.

A bibliography consisting of about one thousand references closes the paper. These references are in the main to forestry literature but they include many to engineering, geological, and geographical works. The literature referred to is chiefly that published in English, French, and German, but several Spanish, Russian, Finnish, and other works are also listed.

F. A. B.

Correlation of Geologic Formations between East-central Colorado, Central Wyoming, and Southern Montana. By W. T. LEE. *U.S. Geol. Survey Prof. Paper 149*, 1927.

The object of the field work, the results of which are given in this paper, was to clear up doubtful points in stratigraphic correlation by

tracing the various formations from range to range, and by making accurate sections at intervals.

The Fountain formation of Colorado was found to be equivalent to the lower part of the Casper formation of the Laramie Basin, and to the lower, or red, part of the Amsden formation of Central Wyoming. The Ingleside formation of Colorado correlates with the Hartville formation to the east, with the upper part of the Casper formation of the Laramie Basin, and with the Upper Amsden and Tensleep formations of Central Wyoming. The Phosphoria formation has formerly been known as the Lower Embar and as the Park City formations. It is correlated with the Satanka shale of the Laramie Basin. The Dinwoody formation, or Upper Embar, is believed to be both Upper Permian and Lower Triassic. Some of the gypsiferous beds of the Owl Creek and Big Horn ranges have been mistakenly included in this formation, but they belong in the Chugwater.

The Lykins formation of Colorado is correlated with the Chugwater of Wyoming. A persistent limestone bed in the midst of the Chugwater red beds is named the Alcova limestone. Knight's Jelm formation is non-marine Upper Triassic. It is correlated with the Popo Agie beds of Central Wyoming.

The Lyons formation is redefined to include only the "Creamy" sandstone bed at Lyons, Colorado. The beds below, which were formerly included in the Lyons, are now placed in the Ingleside formation. The Lyons formation, as redefined, is believed to correlate with the Coconino formation of the Grand Canyon region.

Stratigraphic sections in numerous localities of the area covered by the report are given in the closing pages of the publication.

C. C. B.